Remote estimation of gross primary production and light use efficiency at a boreal bog and an abandoned peatland pasture in western Newfoundland, Canada

By

Syed Shah Mohioudin Gillani

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Abstract

The pristine peatlands store approximately 1/3 of the global soil carbon (C) pool and function as a climate cooling mechanism. A peatland's production is persistently larger than its decomposition due to its high soil water content. However, peatlands disturbed via drainage have been identified as a potential C source. Gross primary production (GPP) and light use efficiency (LUE) are two critical indicators for studying the C budget in terrestrial ecosystems. However, the knowledge of GPP and LUE values in boreal peatlands is still limited because so few measurements have been carried out in peatlands. Field measurements in boreal peatlands cover less than 0.01% of global peatlands; this significantly limits our capacity to understand the C budget of global peatlands. Normally, estimation of the C budget for global peatlands requires field-based measurements to be up-scaled from the field level to the global level. Another commonly-adopted approach for estimating the C budget for global peatlands is to estimate the C budget based on the remotely sensed measurement with global coverage. This approach needs to use the algorithm derived from field measurements. However, there are significant uncertainties over the field-based algorithm used to estimate the GPP and LUE in boreal peatlands due to the very limited availability of field measurements. Moreover, none of the field-based estimations of GPP and LUE were done for drained peatlands. Therefore, more studies are needed to estimate the GPP and LUE for both pristine peatlands and disturbed peatlands based on field measurements. To fill this gap, I conducted a study to estimate GPP and LUE using eddy covariance tower (EC) measurements and MODIS satellite data in a boreal bog and an adjacent abandoned peatland pasture. I have assessed the relationships of GPP with

photosynthetic active radiation (PAR) alone, vegetation indices (normalized difference vegetation index [NDVI] and enhanced vegetation index [EVI]), and their products (PAR×EVI, PAR×NDVI) at both research sites during both study years. The relationship between GPP and the product of vegetation indices and PAR performed better in both study sites, with a greater value of determination coefficient R^2 (0.70 to 0.90), than those calculated from PAR and vegetation indices alone (R^2 ranged from 0.56 to 0.79).

The abandoned peatland pasture had greater LUE capacity than the boreal bog. At the start and end of the growing season, the LUE value was minimum, but in the middle of the growing season, the LUE value peaked at both study sites. The LUE of the abandoned peatland pasture showed greater variations between the study years 2014 and 2015 compared to the boreal bog site. Air temperature and water table depth were the main environmental factors regulating LUE during the growing season in both study years.

Research in this thesis will help to estimate the GPP and LUE in boreal bog and drainage pasture peatlands. This research is important for GPP modeling, and spatial and temporal simulation of GPP and LUE in peatland ecosystems, because both PAR and vegetation indices are readily available from the remotely sensed data. This work will improve our understanding of how GPP and LUE vary over space and time and contribute to C cycle budget and global climate change perceptivity.

Key words: Bog, pasture peatland, light use efficiency (LUE), gross primary production (GPP), vegetation index, normalized difference vegetation index (NDVI), enhanced

vegetation index (EVI), Photosynthetic active radiation (PAR), absorbed photosynthetic active radiation (APAR).

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Chapter 1

1. General Introduction and Overview

1.1. Introduction

Peatlands can be defined as ecosystems in which the rate of net primary production (NPP) has exceeded the decomposition rate over thousands of years, resulting in carbon (C) rich organic matter accumulation (Gorham 1991). Peatland ecosystems have slow decaying organic matter—and their organic matter ranges from 20-87% (Salvador et al. 2014)—along with highly saturated soil, cool soil temperatures, and locations on high latitudes (Dise 2009; Gorham 1991; Roulet et al. 2007). According to Wieder and Vitt (2006), these unique ecosystems have well developed catotelms, their surfaces are mainly covered by bryophytes, and they are influenced by hydrology, climate, and neighboring substrates. Peatland ecosystems are considered a big sink of C soil, but they could also be a C source due to climate change (Dise 2009) and human disturbances. Unfortunately, global warming has greater effects on high latitudes, where the majority of peatlands are located (Christensen et al. 2007). The variation in temperature, rainfall distribution, intensity, and pattern cause changes in the decomposition and respiration rates of peatlands (Gorham 1991). It is assumed that global warming may increase the concentration of carbon dioxide (CO_2) in the atmosphere, which may lead to changes in the process of photosynthesis in plants (Norby et al. 2001). Surface water variables, like water table depth (WTD) and water movement under soil, also affect the C cycle in peatlands (Limpens et al. 2008). Moreover,

nearly 20% of the undisturbed peatlands worldwide have been converted to agricultural soils during the past decade (Joosten and Clarke 2002).

Canada has the world's second largest area covered by peatlands (approximately 1.13 million km^2) after Russia (Tarnocai et al. 2009). Almost 12 % of the area of Canada's peatlands comes under the boreal zone (Tarnocai et al. 2009). Conversion of peatlands and mires to agricultural lands in Canada is a common practice, and nearly 170,000 km^2 of these lands have been converted to agricultural land for cultivation (Joosten 2009). This practice affects the peatlands' light use efficiency and gross primary production.

Light use efficiency (LUE) is defined as the carbon dioxide (CO_2) uptake by vegetation absorbed per unit photon. The use of LUE is common when developing LUE-based models for studying gross primary production (GPP) or net primary production (NPP) globally (Nemani et al. 2003) because a LUE-based model is simple and physiologically based (Goetz and Prince 1999). It is a useful method for linking on-site eddy covariance (EC) measurements of carbon fluxes and remote sensing (RS) data (Yuan et al. 2007a). Understanding vegetation light use efficiency for GPP is relevant to the application of satellite data to monitor GPP and NPP at regional and global levels (Behrenfeld et al. 2001; Running et al. 2000).

GPP is an important parameter to measure the global C cycle because it explains the biomass accumulation in an ecosystem (Gitelson et al. 2008). Generally, the variation of GPP determines the variation of the ecosystem C cycling function, and the GPP magnitude directly determines the magnitude of the carbon uptake function of an ecosystem. It is

important to estimate GPP accurately in order to more precisely examine the C cycling function of an ecosystem. Therefore, ecosystem GPP can be determined by different methods, including direct ground measurements of green biomass production (Bartsch and Moore 1985; Camill et al. 2001; Hirota et al. 2007; Kosykh et al. 2008; Laiho et al. 2014; Moore et al. 2002; Murphy and Moore 2010), C fluctuation (Dimitrov et al. 2011; Grant et al. 2012), or ecosystem modelling (Dimitrov et al. 2011; Harris and Dash 2011). Different studies have reported the effects of different environmental variables (air temperature, water table depth, vapor pressure deficit) on LUE (Connolly et al. 2009b; Heinsch et al. 2003; Syed et al. 2006b). The different models used to measure GPP include the vegetation photosynthesis model (VPM), temperature and greenness (TG), and greenness and radiation (GR) (Sims et al. 2008; Wu et al. 2011; Xiao et al. 2004a). There are limited studies focusing on the LUE and GPP of a drained peatland and their difference compared to natural bog peatlands. I estimated the GPP of a northern peatland ecosystem using MODIS derived vegetation indices (Vis) and field-based photosynthetic active radiation (PAR). Despite recent progress in the use of remote sensing to observe carbon fluxes across ecosystems such as forests and croplands (e.g., Sims et al. 2008; Xiao et al. 2004a), less attention has been given to the application of remote sensing in peatland areas, even though they are a critical component of the carbon cycle (Kross et al. 2016a). Previous studies examined different methods for estimating GPP based on simple parameters, such as VIs alone or PAR alone (Knipling 1970; Sims et al. 2008), but this study explored the potential of estimating GPP as a product of VI and PAR.

1.2. Research objectives

Disturbed pasture peatlands cause changes in plant diversity, species types, and water table depth in peatlands, which can impose remarkable effects on the dynamics of the light use efficiency (LUE), gross primary production (GPP), and their role in the C budget. It has been a huge challenge to predict GPP and measure the LUE in Northern peatlands over a longer period. The existing model applicability at the regional scale is extremely challenging because of its complexity and its requirements of large input data that are mostly inaccessible at the appropriate spatiotemporal scales. The simplest approach to estimate GPP is to derive mathematical functions from a direct correlation between measured GPP and photosynthetically active radiations (PAR) (Olafsdottir and Oskarsson 2014). Many studies were conducted to estimate GPP using PAR and other direct measurements, such as the vegetation index in different ecosystems, but, unfortunately, the northern peatlands were ignored for estimating GPP with this approach. In this study, eddy covariance (EC) data, meteorological data, and Moderate Resolution Imaging Spectrometer (MODIS) data were used to develop a relationship between PAR and vegetation indices (VI) for the estimation of GPP at an abandoned pasture and a boreal bog. Further, EC data and meteorological data were used to estimate LUE for an abandoned pasture and a boreal bog. The specific objectives of my study were:

a) To examine the temporal variations in GPP and PAR.

b) To develop a relationship between GPP and chlorophyll-related VI (Normalized difference vegetation index [NDVI] and Enhanced vegetation index [EVI]).

c) To study the possible relationships between GPP and NDVI× PAR and EVI ×PAR.

d) To investigate the mechanism of changes in LUE in a natural bog and an abandoned peatland pasture during the growing period.

e) To study how LUE varies between a natural bog and an abandoned peatland pasture.

f) To examine the relationship between LUE and air temperature, water table depth (WTD), and vapour pressure depth (VPD).

1.3. Thesis outline

This thesis consists of five chapters.

Chapter 1 is an introductory chapter.

Chapter 2 is the literature review that explains the function of C processes in peatlands, GPP and LUE, and how these are regulated by environmental factors (i.e., air temperature, WTD, and VPD).

Chapters 3 and 4 are the main research chapters, each containing one paper that will be submitted for publication in peer-reviewed journals. Chapter 3 presents the derivation of GPP using VI and PAR at an undisturbed bog and a disturbed pasture peatland. Chapter 4 compares the spatial-temporal dynamics of the LUE in a bog and a pasture peatland and the possible correlation between LUE and environmental factors.

Chapter 5 consists of a conclusion about the important findings from the current research.

Contribution statement

The research objectives and research questions were defined under the supervision of Dr. Jianghua Wu, and research funding was provided by Dr. Jianghua Wu. The raw data used in this thesis was provided by Dr. Mei Wang as part of her PhD thesis research. I analyzed the raw data for my thesis. I wrote the first draft of my thesis and the two manuscripts that are the core of my thesis. Dr. Jianghua Wu comprehensively reviewed and revised my thesis. Dr. Muhammad Nadeem, Mr. Waqas Ali, and my committee member, Dr. Mumtaz Cheema, all commented and edited my first draft.

Chapter 2

2. Literature review

2.1. Peatlands

Peatland can be defined in multiple ways, but most commonly it refers to wetlands that have peat layers. Peat is a mixture of more or less decomposed plant material that has accumulated in high-saturated water conditions and in the absence of oxygen (International Peat Society). In Canada, peatland is defined as a highly waterlogged area with a surface of peat layer exceeding 0.4 m (NWWG 1997). Peatlands consist of both vertical and horizontal arrangements (Belyea 2009). The vertical arrangements have a range of anoxic conditions, mainly controlled by the water table and precipitation (Clymo et al. 1998). Horizontal arrangements of peatlands have small topographic features, called microforms, which show self-organization by producing identifiable and easily observable designs, called hummocks and hollows (Foster and Fritz 1987). Hummocks differ from hollows in terms of vegetation species difference and variation in peat accumulation rates; wetter locations are called hollows (Nungesser 2003).

According to Canadian wetland classification systems, peatlands can be widely divided into two groups: bogs and fens (NWWG 1997). Both have different characteristics in hydrology. Bogs are ombrotrophic, which depend on atmospheric precipitation for nutrients and water input; they have acidic soil, less humus, and often have sphagnum mosses and evergreen shrubs (Bourbonniere 2009; Vasander and Kettunen 2006). Fens are minerotrophic and receive water and nutrients from stream or groundwater and sometimes

receive water from rainfall. These are less acidic, with a higher pH due to water dissolved chemicals, have more humus, and contain dominated vegetation, like graminoid and non-ericaceous shrubs (Chapin et al. 2003; Weltzin J.F. 2000).

Approximately 3 % of the earth's surface is covered by undisturbed peatlands, an area of about 4 x 10^6 km^2 (Gorham 1991). The boreal and subarctic zones occupy around 346 x 10^4 km^2, comprising almost 87% of the global peatlands. There are six countries with more than 5 x 10^4 km^2 area of peatlands: Russia has 142 x 10^4 km^2, followed by Canada 124 x 10^4 km^2 > USA 625 x 10^3 km^2 > Indonesia 27 x 10^4 km^2 > Finland 96 x 10^3 km^2 > and Sweden 7 x10^3 km^2 (Joosten and Clarke 2002). Canada has one of the largest areas of peatland under agricultural use (170000 km^2), but this accounts for only 15% of the total national resources of peatlands and mires.

2.2. The function of peatlands in global C cycle

2.2.1. C pool in peatlands

Carbon (C) is the basic unit of life (Brady and Weil 2008). Globally, soil, atmosphere, vegetation, lithosphere, and hydrosphere are recognized pools for C cycles (Bhatti et al. 2012). The largest terrestrial stock of C is found in the boreal forest (soil and vegetation), and peatlands are linked to them (Bernstein et al. 2008). Northern peatlands presently store almost 1/3 of the worldwide soil C pool, despite covering just 3% of the Earth's surface (Gorham 1991). Northern peatlands act as a C sink due to the disparity among decay and primary production (Gorham 1991).

2.2.2. C exchange rates in peatlands

Net ecosystem exchange (NEE) refers to the net amount of C fixed in the whole ecosystem and is regarded as an important factor in short-term and long-term variations in the worldwide terrestrial C cycle. NEE is determined by the process of gross primary production (GPP) and ecosystem respiration (ER). GPP explains the total amount of C fixed in the process of photosynthesis by plants in an ecosystem, which normally determines the C cycling function of an ecosystem. GPP has a vital role in the global C process and responds to variations in different environmental factors, such as photosynthetically active radiation (PAR), temperature, atmospheric moisture, nutrient availability, and ambient CO_2 concentration. The variation in GPP could influence atmospheric CO_2 concentration and the C cycle (Cox et al. 2000). Although GPP can be directly measured at the site-scale and plot-scale using either an eddy-covariance (EC) technique or a static chamber technique, at a regional or global scale, GPP is commonly estimated from the amount of absorbed photosynthetically active radiation (APAR) and light use efficiency (LUE), as given by the following equation (Monteith 1972)

$$GPP = LUE \times APAR$$

where LUE was considered constant (Monteith 1972). Recently, however, LUE variations were found depending on time and space between ecosystem type, plant species composition, and growing period (Brogaard et al. 2005; Ruimy et al. 1994; Turner et al. 2002). Therefore, LUE is a critical component to correctly estimate GPP and its dynamics. Low temperature, high vapor pressure deficit (VPD), and nutrient stress have been shown

to affect LUE (Running et al. 2004), but water table depth (WTD) is also a key factor that influences photosynthesis in peatlands (Gatis et al. 2016).

2.3. Light use efficiency (LUE)

LUE is defined as the carbon dioxide (CO_2) uptake per unit electromagnetic radiation absorbed by ground cover vegetation. Currently, one of the key research activities of ecosystem biologists is to calculate the photosynthetic C uptake, which is largely affected by LUE, to examine the spatial-temporal variation of LUE among plant species, and to understand environmental factors regulating the variations in LUE (Schulze 2006). The accurate estimation of GPP and/or net primary productivity (NPP) thus needs detailed understanding of the effect of environmental factors on LUE. A lack of knowledge about the effects of environmental factors on LUE hinders further improvement of LUE estimations. The limitations to measuring LUE relate to environmental factors that cause stomatal closure, such as high vapor pressure deficit (VPD), unfavorable temperature, and drought conditions (Landsberg and Waring 1997).

2.3.1. LUE and temperature

Air temperature is one of the key environmental factors that contribute to variation in LUE. The variation in temperature affects the GPP at spring time, when plants start growing, and it also causes variation in annual net C exchange in boreal forests (Black et al. 2000). Connolly (2009b) reported that low temperature reduced the LUE in peatlands. For example, when air temperature approaches -6 to -7^{o}C, LUE is near zero, and when air temperature is below -10^{o}C, LUE is virtually stopped. Heinsch et al. (2003) explained that

LUE is relevant to vegetation during the whole year, that a low temperature affects plants' potential to photosynthesize due to stomatal closure. Temperature and growing degree days (GDD) strongly affect the photosynthetic capacity in peatland ecosystems (Syed et al. 2006b).

2.3.2. LUE and water table depth (WTD)

WTD strongly affects photosynthesis in peatlands, thus affecting the dynamics of LUE. Increases in WTD can cause variation in vegetation cover and the above ground biomass (Murphy and Moore 2010). Water table position and soil moisture affect the photosynthetic efficiency of plants, which in turn affects the LUE (Lafleur et al. 2003). WTD has a positive relationship with photosynthesis: when WTD increases, the photosynthetic process also increases (Gatis et al. 2016). In the western peatland ecosystem, photosynthesis was found to be strongly correlated with WTD (Syed et al. 2006b).

2.3.3. LUE and VPD

High VPD can inhibit photosynthesis by causing stomatal closure (Heinsch et al. 2003). It is stated that when VPD ranges between 1.5 to 2.5 kPa, LUE decreases, and a VPD of more than 2.5kPa stops LUE (Waring et al. 1995). When the VPD increases, it affects the stomatal closure and CO_2 assimilation (Grossnickle and Russell 1991), which influences the photosynthetic process and causes decline in the LUE and GPP.

2.4. Estimation of gross primary production (GPP)

GPP is defined as the total amount of CO_2 that is fixed by plants through photosynthesis. GPP is a key ecological process of terrestrial ecosystems and determines the ecosystem function of C cycling. There are numerous methods to estimate primary productivity, such as ground base measurement, C fluxes measurement, and ecosystem modelling (Dimitrov et al. 2011; Murphy and Moore 2010). It is also feasible to measure carbon fluxes from flux towers to produce regional and global estimates. Remote sensing technology with a global coverage, using time-series satellite images, offers an efficient way to quantitatively evaluate the seasonal differences in GPP in terms of carbon assimilation and biomass on a regional scale. GPP models that use remote sensing inputs follow a theoretical concept of the light use efficiency (LUE) model explained in the following equation (Monteith 1972)

$$GPP = \text{LUE} \times fPAR \times PAR_{in}$$

where *f*PAR represents fraction photosynthetically active radiation and PARin represents incident PAR .

Deriving LUE from this GPP model is challenging. In most of the LUE models, LUE is expressed as a biome-specific constant at its potential maximum, adjusted for unfavourable environmental conditions (e.g. limitations of temperature, humidity, soil moisture, etc.) (Nouvellon et al. 2000; Veroustraete et al. 2002). Recently, another approach has been proposed to estimate GPP, essentially a modified version of Monteith's model, and one that does not need independent estimates of the *f*APAR and the LUE terms. Since chlorophyll is involved in the photosynthetic process, it is crucial for primary production and is

conceptually related to GPP (Sellers et al. 1992). Previous studies have suggested that GPP can be predicted by direct correlation with vegetation indices related to chlorophyll (Gitelson et al. 2008; Harris and Dash 2011).

However, these models are not good for high frequency GPP variations due to changing illumination conditions. Some studies have modelled GPP as the product of VIs and the incident PAR (Gitelson et al. 2006; Peng et al. 2013; Wu et al. 2009). Schubert et al. (2010) also showed that the product of PAR and satellite sensor-derived EVI could be used to describe the GPP variabilities in peatland ecosystems. Peng et al. (2013) also reported that the product of VIs (NDVI, EVI), and PAR exhibited a higher determination of coefficients R^2 for the GPP estimation. Sim et al. (2008) used a similar method for a temperature and greenness model to estimate GPP, and concluded that the EVI×LST (land surface temperature) model is useful as a proxy for PAR and EVI. GPP in northern peatlands is influenced by PAR, WTD, and vegetation phenology (Helfter et al. 2015b; Nijp et al. 2015b; Sulman et al. 2010a); therefore, a combination of PAR, WTD, and vegetation phenology can be used to estimate GPP variation in northern peatlands.

2.4.1. GPP and PAR

Photosynthesis is influenced by PAR that facilitates C fixation and assimilation processes. PAR and GPP have a positive and a strong relationship in such ecosystems as the peatlands (Nijp et al. 2015b; Schubert et al. 2010). The vegetation productivity is dependent on the amount of solar radiation absorbed in the plant canopy (Knipling 1970). A mathematical

function derived from direct correlation between measured GPP and PAR is a simple way to estimate GPP. Monteith (1972) explained that GPP is the product of a fraction of absorbed photosynthetically active radiation (fAPAR), incident PAR (PARin), and light use efficiency (LUE). Many models of GPP estimation have been developed since then. Consequently, PAR is a key input for GPP modeling in peatland ecosystems as well (Schubert et al. 2010).

2.4.2. GPP and WTD

Soil water plays a key role in plant growth. Numerous studies have reported that during drought periods, the GPP is minimized because of stressful conditions on plant productivity (Chivers et al. 2009; Weltzin J.F. 2000). During drought conditions, GPP responds differently in fens and bogs, in that GPP is reduced at fens but increased at bogs during wetter conditions, because of variation in the relative contributions of vascular species and mosses (Sulman et al. 2010a). However, some studies reported that lower water level can increase GPP by enhancing vegetation productivity and nutrient availability for plant uptake (Gorham 1991; Munir and Strack 2014; Weltzin J.F. 2000).

2.4.3. GPP and vegetation phenology

Vegetation phenology has a key role in CO_2 flux in peatlands (Helfter et al. 2015b). It is reported that at the start of the growing season, there is a sharp increase in GPP in peatlands (Kross et al. 2014). Furthermore, the spatial and temporal variation in GPP is determined by the growing season length (Helfter et al. 2015b).

2.4.4. GPP and VI (NDVI and EVI)

Satellite remote sensing has played an important role in the characterization of vegetation structure and the estimation of GPP or net primary production (NPP) by providing reliable and systematic observations of vegetation and ecosystems. Satellite remote sensing can overcome the dearth of extensive flux tower observations over large areas (Behrenfeld et al. 2001).

According to Sims et al. (2008) the simplest possible model would be a direct correlation between GPP and vegetation indices. The remote estimation of crop chlorophyll content to assess mid-day GPP ranged from 0 to 3.1 mg $CO2/m^2s$ in maize and soybean (GPP ranged from 0 to 1.8 mg $CO2/m^2s$) under different environmental conditions (Gitelson et al. 2006). It has already been shown by several studies in various environments that eddy covariance GPP and EVI have consistent, linear relationships, while NDVI has little seasonal variation or a weak relationship with GPP (Huete et al. 2008; Xiao et al. 2004a).

A simple model was suggested to relate crop GPP to a product of chlorophyll-related vegetation indices (VI) and incoming photosynthetically active radiation (PARin) (Gitelson et al. 2006; Peng and Gitelson 2011; Wu et al. 2009). The VI-PARin based model had shown the ability to predict GPP in crops using MODIS and MERIS data (Boyd et al. 2012; Wu et al. 2009). The widespread acceptance of NDVI, as a substitution for chlorophyll content, and its use at both ground and remote levels, make it a suitable option for use in the prediction of ecosystem productivity (Gutma 1998).

Chapter 3

3. Estimating gross primary production in boreal peatlands using the measured photosynthetically active radiation and MODIS - derived vegetation index .

3.1. Abstract

Gross primary production (GPP) is the amount of carbon fixed during photosynthesis by all producers in the ecosystem. GPP usually has a significant correlation with i) photosynthetically active radiation (PAR); ii) different vegetation indices (VIs), including the normalized difference vegetation index (NDVI); or iii) enhanced vegetation index (EVI). Therefore, GPP can be estimated using PAR, VIs, or a combination of them. In this study, I have evaluated and compared the efficacy and performance of five different relationship models using PAR, NDVI, EVI, PAR×NDVI, PAR×EVI to estimate the GPP in a bog and a pasture peatland in western Newfoundland, Canada. The VIs were derived from a Moderate Resolution Imaging Spectroradiometer (MODIS), whereas actual field-based GPP was measured by using the eddy covariance technique; the PAR data were obtained from PAR sensors. The results revealed that the PAR×EVI model was significantly superior to predict GPP by expressing a higher coefficient of determination compared to other models at both study sites during 2014-2015. Results further confirmed EVI as a better indicator of GPP estimation, either alone or as a combination of EVI × PAR. The study results offer a useful and efficient approach for predicting GPP by using remotely sensed data for boreal peatlands and drained peatlands.

Keywords: Enhanced vegetation index (EVI), Gross primary production (GPP), northern peatlands, Moderate resolution imaging spectroradiometer (MODIS), vegetation indices (VIs), photosynthetically active radiation (PAR), Normalized difference vegetation index (NDVI), Enhanced vegetation index (EVI).

3.2. Introduction

Peatlands are carbon (C) rich ecosystems and play an important role in global C cycling. The North American continent holds about 1,735,000 square kilometers of peatlands (Boelter 1977)--and approximately 60% of those peatlands are in Canada (Tarnocai 2009)--of which 2000 square kilometers is distributed in Newfoundland and Labrador (NL) (South 1983). Currently, northern peatlands store nearly one third of the global soil C pool, despite covering only 3% of the land surface area (Gorham 1991). The estimated C pool of northern peatlands ranges from 234 to 547 Pg C (Armentano and Menges 1986; Gorham 1991; Lappalainen 1996; Turunen et al. 2002; Yu et al. 2010). Natural peatlands tend to be carbon dioxide (CO_2) sinks and methane (CH_4) sources; hence, peatlands have acted to cool global climate for the past several millennia by sequestering around 20-30 g C m^{-2} yr^{-1} from the atmosphere, mainly due to slow decomposition rates of peat organic matter under water-logged conditions (Gorham 1991; Turunen et al. 2002; Wang et al. 2014; Yu et al. 2010).

Gross primary production (GPP) is the total amount of C absorbed by an ecosystem via photosynthesis; thus, GPP largely determines the inputs of plant organic matter into an ecosystem, and is arguably an important ecological function of C cycling in an ecosystem. GPP is a key parameter for measuring the global C cycle and explains the biomass

accumulation in any ecosystem (Gitelson et al. 2008). Usually, the variation of GPP determines the variation of an ecosystem's C cycling function, and the GPP magnitude directly determines the magnitude of an ecosystem's carbon uptake function. An accurate estimation of GPP is crucial to the examination of the C cycling function of an ecosystem within the context of climate change and human disturbances. Ecosystem GPP can be measured in several ways, including direct ground measurements of green biomass production (Bartsch and Moore 1985; Camill et al. 2001; Hirota et al. 2007; Kosykh et al. 2008; Laiho et al. 2014; Moore et al. 2002; Murphy and Moore 2010), C fluctuation (Dimitrov et al. 2011; Grant et al. 2012), or ecosystem modelling (Dimitrov et al. 2011; Harris and Dash 2011).

It is important to understand the quantitative estimation of the spatial and temporal variation of GPP from small to large-scale areas and to know how an ecosystem behaves under different atmospheric CO_2 concentrations (Coninck et al. 2005). GPP in northern peatlands is mainly controlled by photosynthetically active radiation (PAR), hydrologic and thermal conditions, availability of nitrogen (N) and phosphorus (P), and plant phenology and diversity (Helfter et al. 2015a; Lund et al. 2009; Nijp et al. 2015a; Sulman et al. 2010b). GPP in any ecosystem is measured either through ground-based measurements or through different remotely sensed vegetation indices, as proposed by Monteith (1972). However, the field-based GPP measurement involves extensive fieldwork with destructive plant samplings and, normally, can only cover a small area where the direct measurement is made. To overcome these challenges of field-based plant sample difficulties and small spatial coverage, the most common practice is to use remote sensing data involving

nondestructive sampling to model the field-based GPP at a larger scale. Monteith (1972) proposed that GPP can be calculated as the product of the fraction of absorbed photosynthetically active radiation (*f*APAR), PAR, and light use efficiency (LUE), as described below:

$$GPP = fAPAR \times PAR \times LUE$$

However, most C exchange models depend on remote sensing methods and require maximum input from field-based climatic data and vegetation types. For instance, the Vegetation Photosynthesis Model (VPM) assumes that leaf and forest canopies consist of photosynthetically active vegetation and non-photosynthetically active vegetation. This model performed well for the estimation of GPP in forest ecosystems, such as in alpine, tropical, and needle evergreen forests (Xiao et al. 2004a). Furthermore, the VPM is being used to estimate GPP in agricultural ecosystems (Yan et al. 2009). Light use efficiency (LUE) is another remote sensing model being used to measure the GPP over a large scale; however, LUE values need to be adjusted due to their effects on the model accuracy (Yuan et al. 2007b). Spatial and temporal LUE variations are the main constraints in determining an accurate GPP, as noted by Turner et al. (2003). However, such data sets are not available at the same space and time as the other remote sensing data. Such variations could invite substantial error into the estimation of C exchange in an ecosystem (Yuan et al. 2007b). As a result, it is important to develop models that are entirely based on remote sensing (RS) data. The temperature and greenness (TG) model depended only on the RS-derived enhanced vegetation index (EVI) and the land surface temperature (LST) from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Sims et al. 2008). The

simplest approach to estimate GPP would be to derive GPP values mathematically from its direct correlation with PAR (Olafsdottir and Oskarsson 2014). The easiest possible model would be a direct correlation between VIs and GPP. The product of PAR and chlorophyll-related vegetation indices ($GPP \propto VI \times PAR$) could be used for the estimation of crop GPP (Gitelson et al. 2012). Several vegetation indices are known for their estimation of chlorophyll content, including the normalized difference vegetation index (NDVI), the red edge chlorophyll index (CI_{red} edge), the MERIS terrestrial chlorophyll index (MTCI), and the modified simple ratio (MSR) (J. W. Rouse et al. 1974; Sims and Gamon 2002; Wu et al. 2009; Yan et al. 2009). GPP in maize (Zea mays L.) and soybean (Glycine max L.) field crops were successfully estimated with the product of PAR and NDVI (Gitelson et al. 2006). The same model was confirmed by Wu et al. (2009), where GPP could be estimated from PAR.

Schubert et al. (2010) used three years of eddy covariance data from two peatlands in Sweden, averaged for 16-day composite periods, related to data from the MODIS, and modeled photosynthetic photon flux density (PPFD).

The NDVI showed saturation during summer time, and the EVI generally gave better results in explaining GPP in northern peatlands. The potential of chlorophyll-based vegetation index models to estimate peatland GPP from satellite data was demonstrated by Harris and Dash (2011) using satellite data specifically related to vegetation chlorophyll content, which may ultimately facilitate improved quantification of peatland carbon flux dynamics. The potential for MODIS data to monitor the C dynamics of northern peatlands was examined by Kross et al. (2013). Rahman et al. (2005) suggested that EVI could be

used to provide reasonably accurate direct estimates of GPP on a truly per-pixel basis in North American vegetation.

Satellite sensor-derived data had previously been used in regression models for GPP estimation in various ecosystems, such as agriculture, grasslands, and forests (Olafsdottir and Oskarsson 2014; Wu et al. 2009; Xiao et al. 2004c). There is a need to search for similar relationships for other ecosystems, such as peatlands, which will be helpful in carrying out large-scale monitoring of CO_2 exchange. Assuming the same relationships apply to all ecosystems could result in over or underestimation of CO_2 exchange at the local or global scales. Hence, the objective of this study is to determine the possibility of using satellite derived data and PAR in regression models for GPP calculation in peatlands.

Therefore, this study was conducted with the following objectives:

a) To determine the variations in GPP and PAR.
b) To develop a relationship between GPP and chlorophyll-related VI (NDVI and EVI).
c) To study the possible relationships between GPP and NDVI× PAR and EVI ×PAR.

3.3. Methodology

3.3.1. Study sites

Experimental sites were located near Robinsons (48.264º N, 58.665º W) on the west coast of Newfoundland, Canada. According to the closest meteorological station at Stephenville (48.260 º N, 58.55 º W), the mean yearly precipitation was above 1000mm and the mean

air temperature was above 5 °C for the last 30 years (1981-2010). During the 2014 and 2015 growing season, the mean air temperature was 12 °C and the rainfall was 600 mm. The experimental sites were a part of a peatland complex and were comprised of a peatland pasture (agriculturally drained peatland) and an undisturbed natural peatland (bog). The agriculturally drained peatland was an undisturbed natural peatland before the 1970s and was drained by ditches (0.5 m deep and 0.3 m wide with a spacing distance of 20-30 m) to convert it into a disturbed pasture peatland. Pasture fodder grasses were introduced at the time of drainage. However, this site was left unmanaged after 10 years of management with active drainage. The undisturbed natural peatland is classified as a bog peatland and was situated close to the east of the pasture site (Figure 3.1). Such a bog is representative of peatlands in eastern Canada, with a constituent of hummocks, hollows, and pools, and it was dominated by bog moss with gray reindeer lichens. Sedges and shrubs were the dominant species in the hollows and hummocks, respectively. The maximum covering shrub species were *Rhododendron* and *Gaylussacia*, whereas the main species of sedge was *Trichophorum Cespitosum L*. The disturbed peatland pasture was covered by canary grass (*Phalaris sp.*), herbaceous species (*Carex*, *Hieracium and Ranunculus species*), numerous shrubs (*Myrica, Lonicera, Photinia sp.*), and different graminoids.

3.3.2. PAR measurement

The study sites were equipped with a pair of eddy covariance (EC) towers, one each at the pasture and the bog site, at a height of 3.4 m from ground level (Figure 3.1). The point quantum sensors (LI-190sl-50, LI-COR Inc., Nebraska, USA) were mounted on the EC towers for continuous PAR recordings, and this PAR data were used in the GPP

measurements in the current study. The EC towers were also equipped with two quantum sensors, where the upper side of the sensors measures the incoming PAR, and the lower side measures the reflected PAR. The sensors scanned at 5-s intervals and recorded at the half-hour PAR_{in} data during daytime; a 16-day average was calculated for the current study.

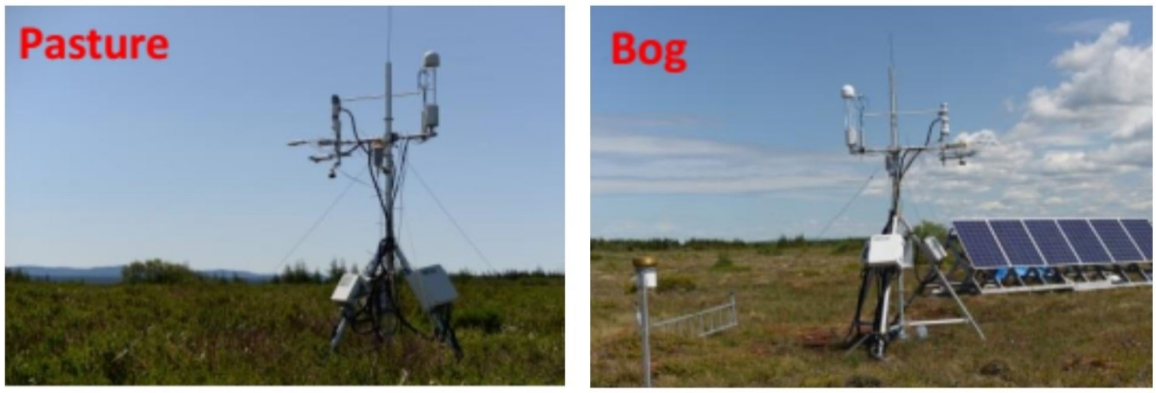

Figure 3.1: The location of the EC towers at the bog and at the pasture peatlands in Robinsons, Western Newfoundland, Canada.

3.3.3. GPP measurements

EC towers were also equipped with a three-dimensional sonic anemometer to measure wind speed and direction, whereas the infrared gas analyzer recorded the variations of CO_2 and H_2O in molar densities. The distance between the sonic anemometer and the gas analyzer was 0.03 m East and Northside, 0.23 m perpendicular to the bog. However, this distance was 0.07 m East and Northside, and 0.16 m vertical to the pasture site. The diaphragm pump pulled the air, with the help of a long sample tube, into the gas analyzers at the rate

of 16.07 L min^{-1} at the bog, and 16.73 L min^{-1} at the pasture site. The concentrations of CO_2 and H_2O inside the sampling cell were measured, along with temperature and pressure. The raw data were recorded at 10 Hz using a portable USB drive, and was then processed to 30 min output flux data. GPP was not a direct measurement from EC systems. For both sites (pasture and bog) where GPP estimates were not available, ecosystem respiration (ER) was estimated using the following equation, suggested by Wang et al. (2018)

$$ER(T) = ER_{ref} \times e\,E0 \left[\frac{1}{(T_{ref} - T0)} - \frac{1}{T - T0}\right]$$

where T_{ref} is set as 10 ºC, T0 is fixed at -46.02 ºC and E0 is the activation energy parameter. ER_{ref} represents the ecosystem respiration at the reference temperature. GPP was then determined from the following equation

$$GPP = ER - NEE$$

where NEE is the net ecosystem CO_2 exchange measured by the EC system.

3.3.4. Data processing

The EddyPro 5.2.1 software (Li-COR, Lincoln, NE, USA) was used to process the 10 Hz data, and outcomes were over a 30-min interval of CO_2 and H_2O fluxes. I used gap-filled data to calculate 16-day averages at both EC towers; GPP data for each daytime 30-min interval were then averaged over each 16-day interval. An online data tool was used for

filling the data gaps for CO_2 flux(http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/), as suggested by Falge et al. (2001). The GPP data used in this study were calculated by the average of the 16-day periods because the MOD13Q1 data, such as the normalized differential vegetation index (NDVI) and enhanced vegetation index (EVI), were only available bi-weekly.

3.3.5. MODIS products acquisition

MODIS contains the Terra and Aqua satellite with 36 spectral bands ranging from 450 to 2100 nm. The vegetation index data were downloaded for the 16-day intervals from MODIS product (MOD13Q1 http://daacmodis.ornl.gov/cgibin/MODIS/GLBVIZ_1_Glb/modis_subset_order_global_col5.pl). In the MOD13Q1 product, the NDVI and EVI dataset were available at 250 m resolution. The MOD13Q1 product data were obtained during the 2014 and 2015 growing seasons (May- October). The pixel of 250×250 m was located inside the border of the bog research site. At the pasture site, only 1-2 % of the pixel was outside its border.

3.3.6. Normalized Difference Vegetation Index (NDVI)

The most extensively used and known vegetation index is the NDVI, described by Rouse Jr et al. (1974). The NDVI depends upon the red and near-infrared spectrum, due to chlorophyll pigments and leaf cellular structure, which can be calculated by the formula given below:

$$NDVI = \frac{NIR-RED}{NIR+RED}$$

where NIR is near infrared and RED describes the red region in spectral reflectance. However, it is well known that NDVI has some constraints with saturation in dense canopy and is sensitive to soil background and atmospheric vaporizer influence (Huete et al. 2002). The NDVI is directly related to the photosynthetic capacity and energy absorption by plant canopies (Myneni et al. 1995).

3.3.7. Enhanced Vegetation Index (EVI)

Huete et al. (1997) developed the EVI index, which is an improved vegetation index of the vegetation information with higher sensitivity in greater biomass area. The EVI index uses the blue bands for soil variable and canopy background reflectance (Huete et al. 1997). The blue wave band of EVI directly reduces the reflectance in the red wave band, and EVI is calculated by the following formula:

$$\mathrm{EVI} = \mathrm{G} \times \frac{(\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + \mathrm{C1} \times \mathrm{RED} - \mathrm{C2} \times \mathrm{Blue} + \mathrm{L})}$$

where G is a gain factor of 2.5, and the difference between NIR and RED represents energy exchange through a canopy. C1 and C2 represent the coefficient of aerosol reflectance. Blue is an atmospheric corrected surface reflectance for the blue band of visible light, and L stands for canopy background reflectance.

3.4. Results

3.4.1. Temporal variation of GPP and PAR

GPP and PAR_{in} indicated temporal variations throughout the growing season at the pasture and bog experimental sites during both study years (Figure 3.2-3.3). GPP showed a great increase at the start of growing season, reached a plateau during the middle of the growing season, and decreased thereafter during the 2014 and 2015 study years, as depicted in Figure 3.2. Comparing the two years of GPP data showed similar trends throughout the growth period at the pasture site (Figure 3.2). However, PAR showed different patterns during the first half of the growing seasons (Figure 3.2); higher PAR values were observed at the start of the growing seasons during both years. Thereafter, a decrease in PAR values was observed until the end of the growing seasons (Figure 3.2). When I compared GPP and PAR values, it was obvious, as shown in Figure 3.2, that both sites did not follow similar patterns during the first half of the growing season, but both decrease thereafter (Figure 3.2).

The bog site showed somewhat similar patterns for the GPP during both study years when compared to the pasture site (Figure 3.3): there was an increase in GPP at the start of the growing seasons; its highest GPP values were during the middle of the growing seasons; thereafter, a decline in GPP values was observed (Figure 3.3). However, PAR did not show similar trends when compared with the pasture site during 2014 and 2015, as shown in Figure 3.3. Higher PAR was noticed at the start of the growing season of 2014, whereas

maximum PAR was recorded near the middle of the growing season during 2015, showing different patterns in PAR at the bog site (Figure 3.3).

When comparing the pasture and bog sites, I noted that maximum PAR and GPP values were recorded at the pasture site during 2014 (Figure 3.2-3.3). During 2015, PAR values were higher and GPP values were lower at the bog site than at the pasture site. Overall, the GPP value was higher in the pasture site than the bog site during both the 2014 and 2015 study years.

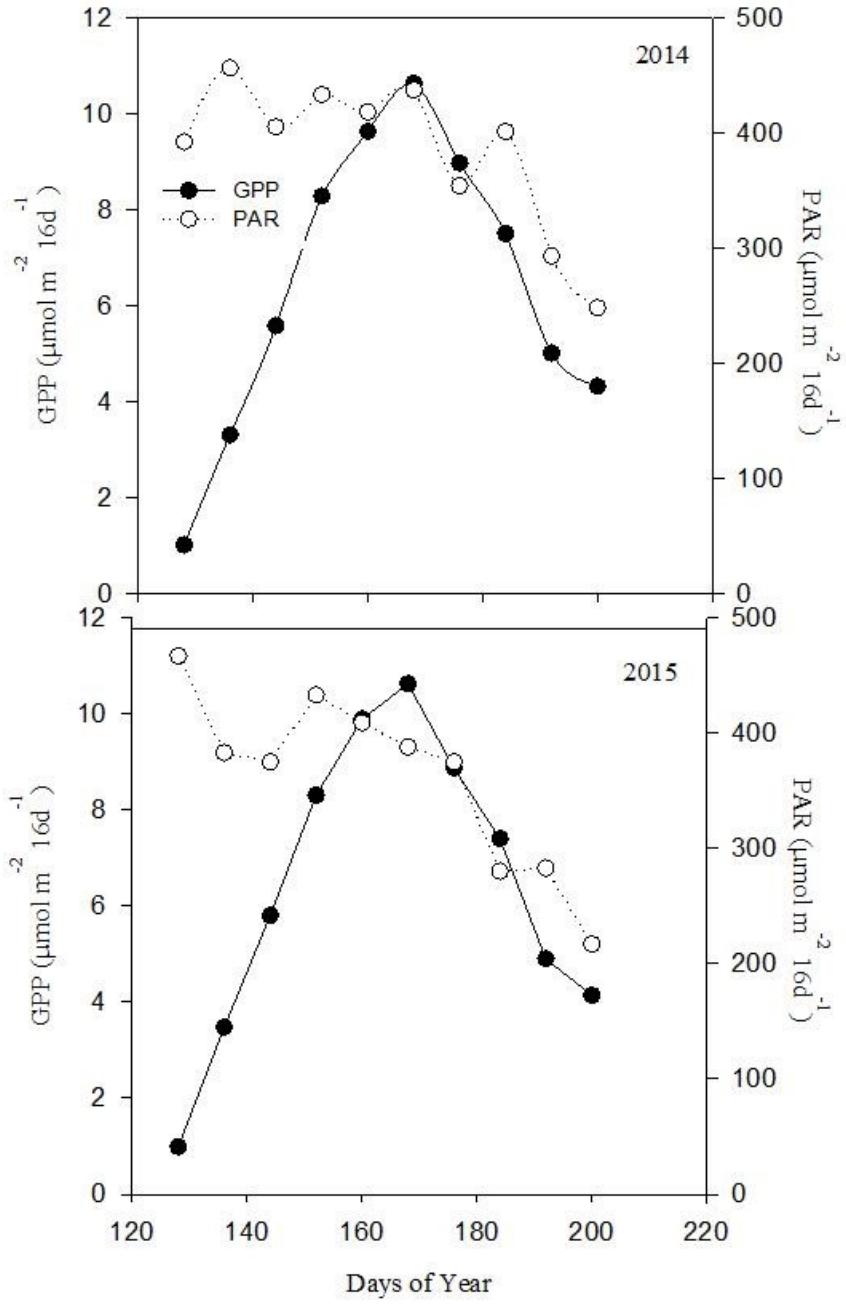

Figure 3.2: Temporal variations in GPP (●) and PAR (○) measured by the EC tower during the 2014 and 2015 growing seasons at the pasture site in western Newfoundland, Canada.

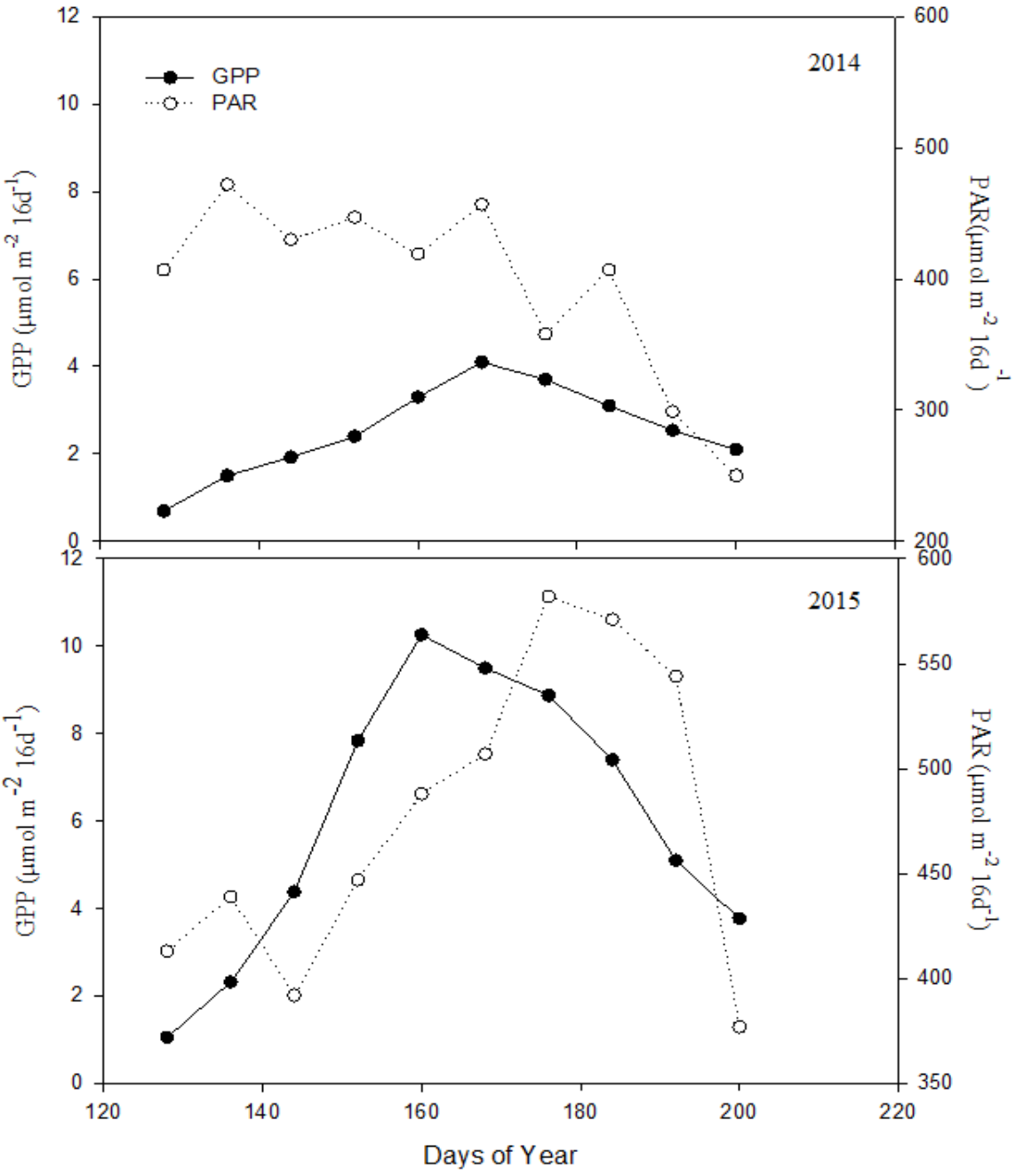

Figure 3.3: Temporal variations in GPP (●) and PAR (○) measured by the EC tower during the 2014 and 2015 growing seasons at the bog site in western Newfoundland, Canada.

3.4.2. Temporal variations in NDVI and EVI

At the start of the growing season in both study years, both VI values increased significantly, reaching maximum values during the middle of the growing seasons, and decreasing thereafter. Similar temporal patterns were observed in the NDVI and EVI profile during the 2014 and 2015 growing seasons at the pasture site .The NDVI values varied between 0.50 and 0.90, whereas the EVI values ranged between 0.30 and 0.70 (Figure 3.4).

Similar temporal patterns were observed in the NDVI and EVI profile during the 2014 growing season at the bog site (Figure 3.5). Early in the growing season, both VI values increased significantly, reaching maximum values during the middle of the 2014 growing season, and decreasing thereafter (Figure 3.5). NDVI values varied between 0.50 and 0.80, whereas the EVI values ranged between 0.30 and 0.55 during 2014 (Figure 3.5). In 2015, the NDVI again followed similar temporal patterns as 2014, but the EVI values showed differences. The EVI values fluctuated during the middle of the 2015 growing season. That same year, the NDVI values varied between 0.50 and 0.80, whereas the EVI values ranged between 0.25 and 0.50 (Figure 3.5)

The NDVI and EVI indices followed similar variation patterns at the pasture site, but they did not follow the same trends at the bog site during both study years (Figure 3.4-3.5). NDVI expressed significantly higher values than EVI at the pasture and bog sites during both study years (Figure 3.4-3.5).

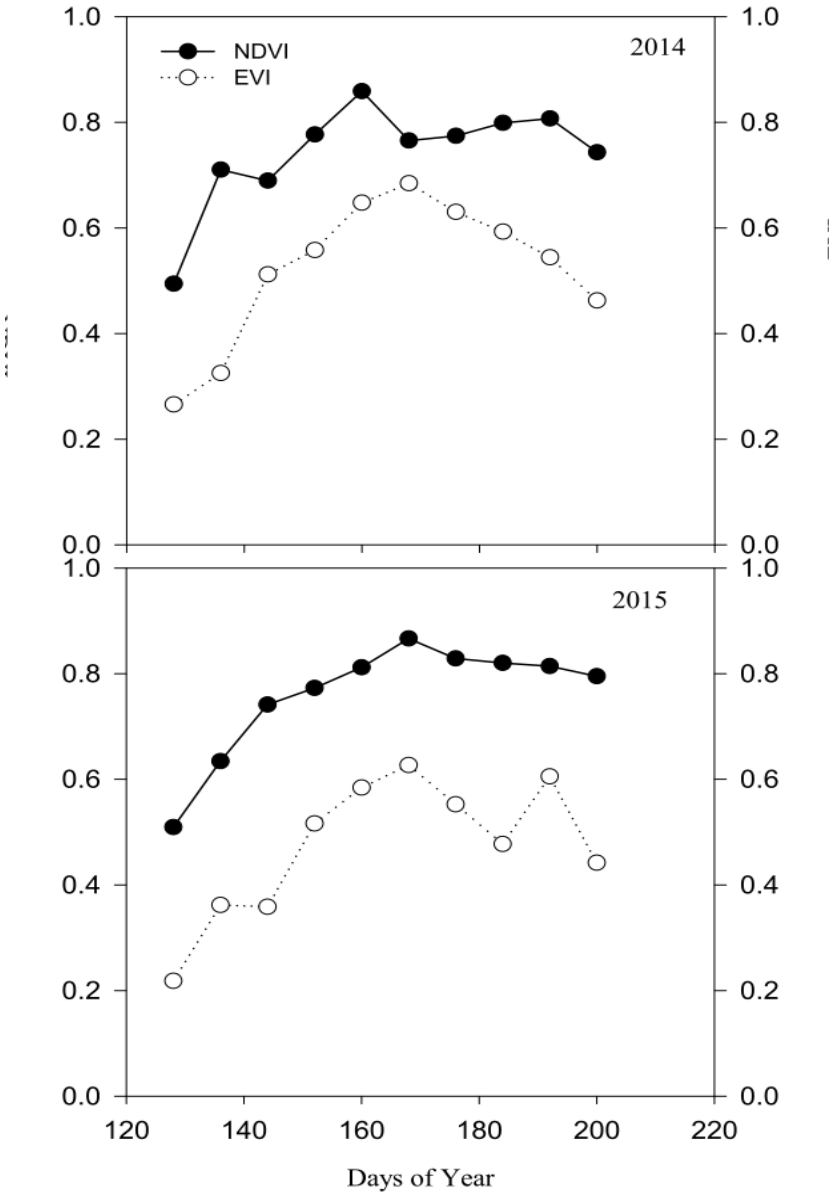

Figure 3.4: Temporal variations in NDVI (●) and EVI (○) derived from MODIS, during the 2014 and 2015 growing seasons (May-October) at the pasture site in western Newfoundland, Canada.

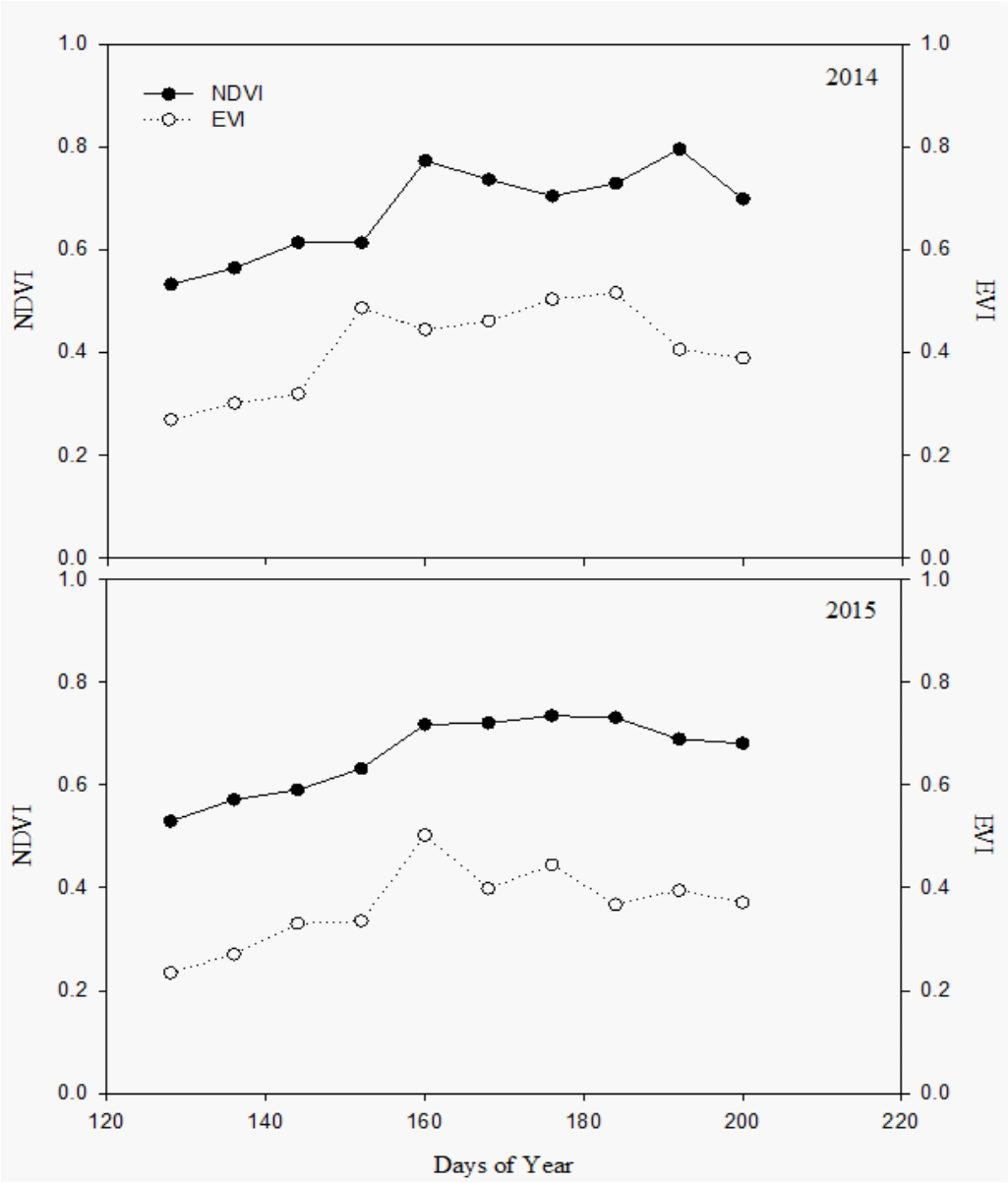

Figure 3.5: Temporal variations in NDVI (●) and EVI (○) derived from MODIS, during the 2014 and 2015 growing seasons (May-October) at the bog site in western Newfoundland, Canada.

3.4.3. GPP relationship with PAR and VIs

After evaluating the extent of the GPP relationships with PAR alone, with other vegetation indices (NDVI, EVI), and their products (PAR×NDVI, PAR×EVI), at both the pasture and the bog sites during both study years, a significant positive correlation was found between PAR and GPP at the pasture site (Figure 3.6). However, Pearson's correlation was significantly higher at the pasture (R^2 = 0.51 and 0.47) than at the bog (R^2 = 0.46 and 0.37) during both study years. A weak and non-significant correlation was obtained at the bog during 2015, as shown in Figure 3.6.

To assess the degree of the GPP's relationship with other vegetation indices, I drew a correlation of GPP with NDVI and EVI alone. The GPP had a significantly ($P<0.05$) positive correlation with NDVI and EVI during both study years at both sites (Figure 3.7-3.8). However, there are apparent differences in GPP and VI correlations at the pasture and bog sites the EVI showed strong positive correlations with the GPP, where R^2 values ranged from 0.68** to 0.79** for the pasture and 0.71** to 0.72** for the bog, as depicted in Figure 3.8; however, the NDVI expressed a significantly lower correlation relationship with the GPP at both sites (Figure 3.7). Pearson's correlation values between GPP and NDVI ranged from 0.56** to 0.66** for the pasture, and 0.59** to 0.67** for the bog (Figure 3.7).

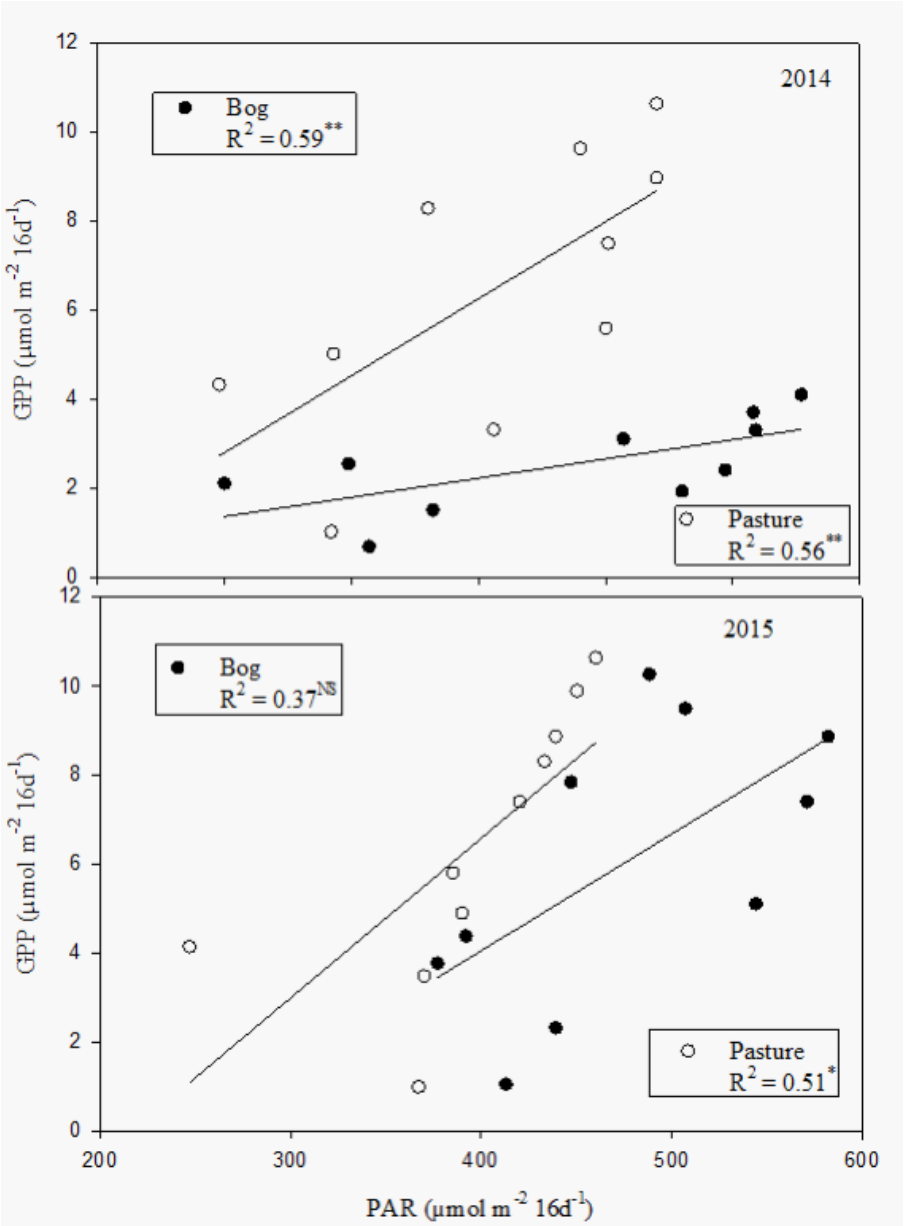

Figure 3.6: Relationship between the EC tower-based GPP and PAR during the 2014 and 2015 growing seasons (May-October) at the bog and the pasture sites in western Newfoundland, Canada.

Asterisks indicate significance level of the relationship: *P <0.05

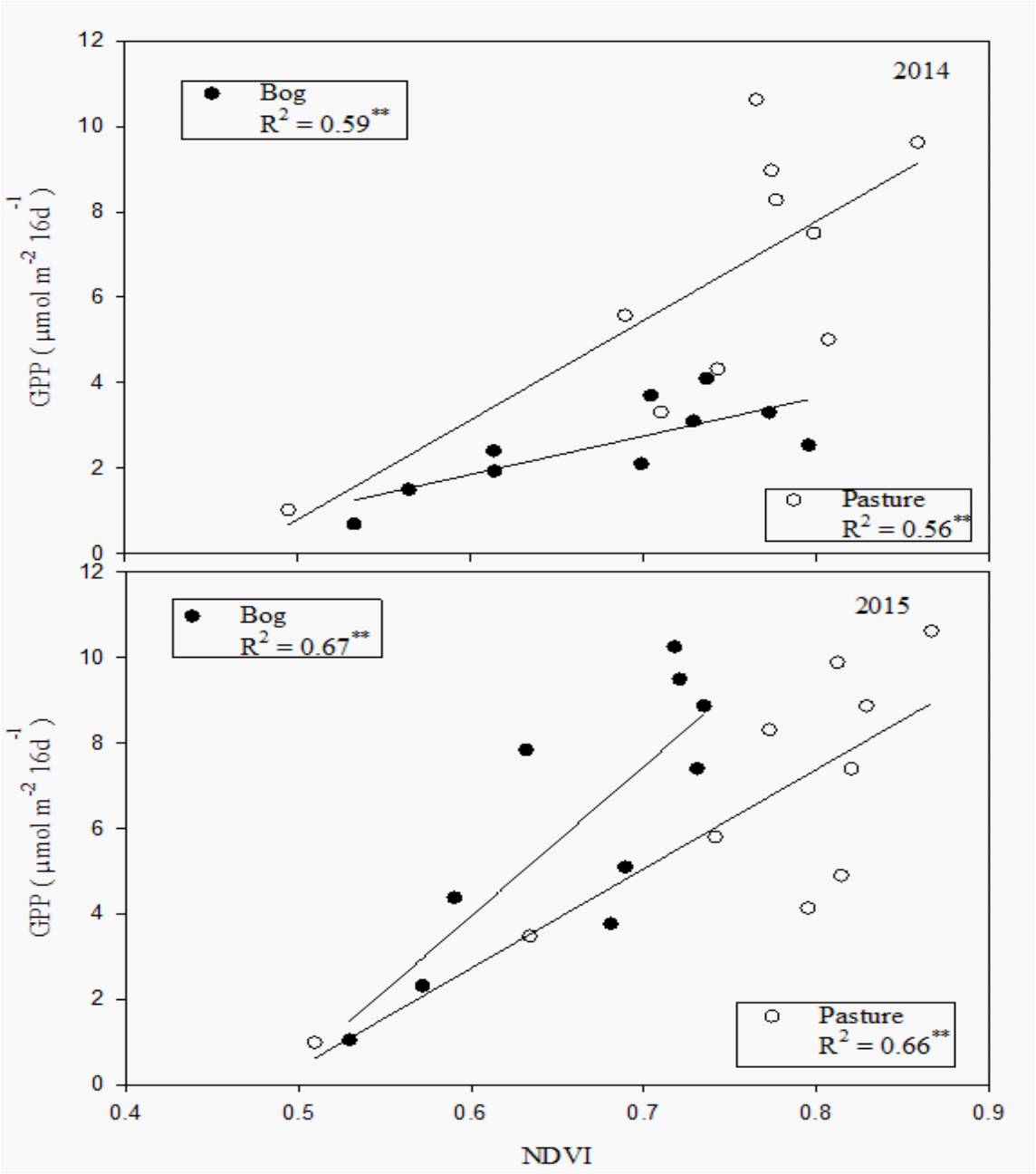

Figure 3.7: Relationship between the EC tower-based GPP and NDVI derived from MODIS, during the 2014 and 2015 growing seasons (May-October) at the bog and pasture sites in western Newfoundland, Canada.

Asterisks indicate significance level of the relationship: **P < 0.01

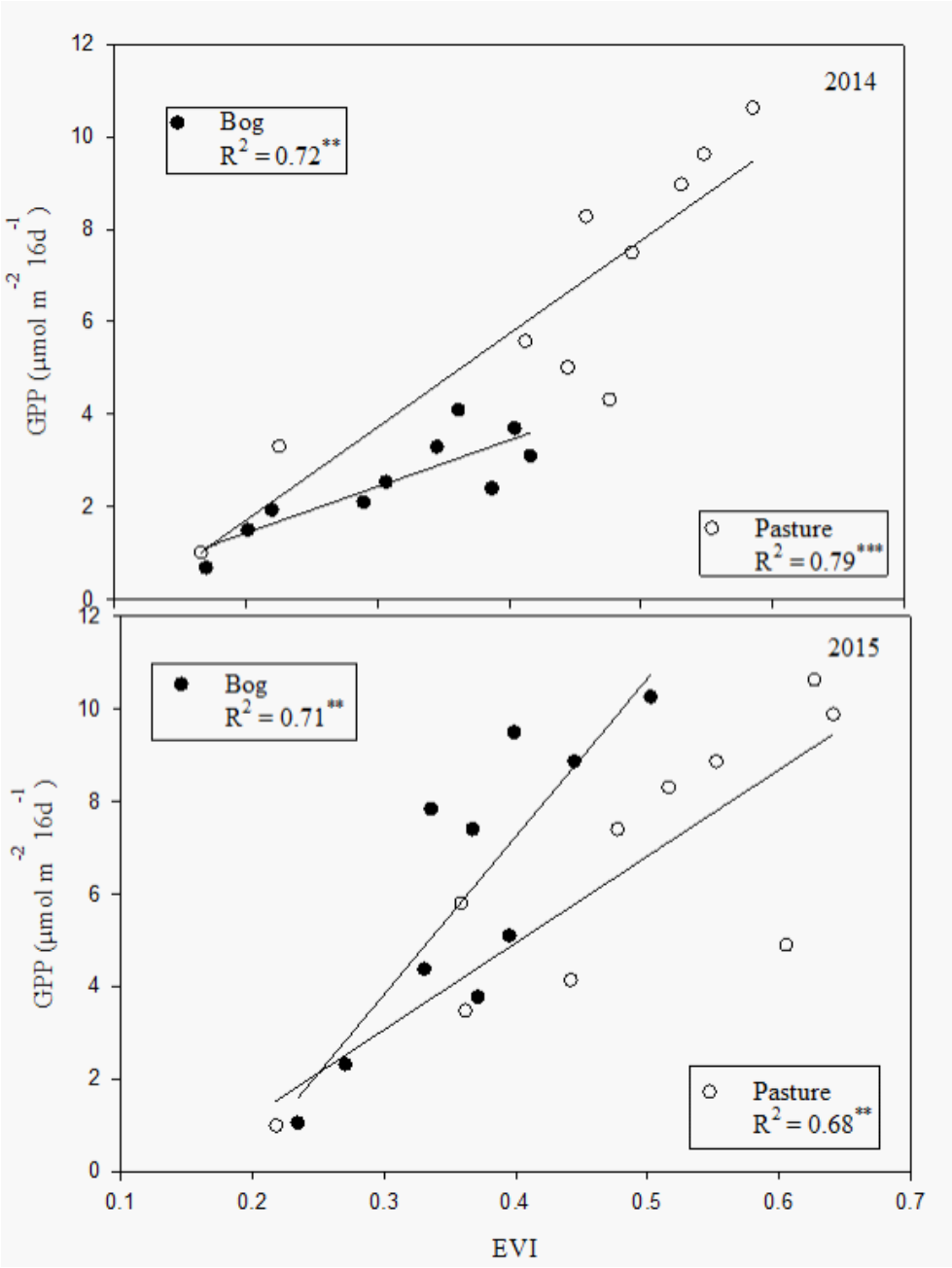

Figure 3.8: Relationship between the EC tower-based GPP and EVI derived from MODIS, during the 2014 and 2015 growing seasons (May-October) at the bog and pasture sites in western Newfoundland, Canada.

Asterisks indicate significance level of the relationship: **P < 0.01, ***P <0.001

3.4.4. GPP relationship with the product of PAR and VIs

To evaluate the efficacy of VIs and PAR to predict GPP at the pasture and bog sites, I examined the correlation coefficient among the product of PAR×VIs and GPP during both study years (Figure 3.9-3.10). The product of PAR and VIs-- for instance, PAR×EVI and PAR×NDVI-- significantly improved the prediction efficacy of the GPP variations compared to PAR or VIs alone, at both study sites (Figure 3.9-3.10). PAR×NDVI expressed significantly higher positive correlations with GPP at both study sites; however, the correlations were significantly stronger in 2015 (pasture 0.76***, bog: 0.75***) compared to 2014 (pasture: 0.69**, bog: 0.68**), as depicted in Figure 3.9. PAR×EVI showed significantly positive correlations with the GPP at both study sites during 2014 and 2015 (Figure 3.10). The strength of correlation between the GPP and PAR×EVI was significantly higher at the pasture (0.89*** in 2014, 0.81*** in 2015) and bog (0.83*** in 2014, 0.90*** in 2015) sites (Figure 3.10) than the correlation between the GPP and PAR×NDVI. The PAR×EVI (Figure 3.10) expressed significantly higher GPP prediction efficacy compared to PAR×NDVI (Figure 3.9) during both study years at both study sites.

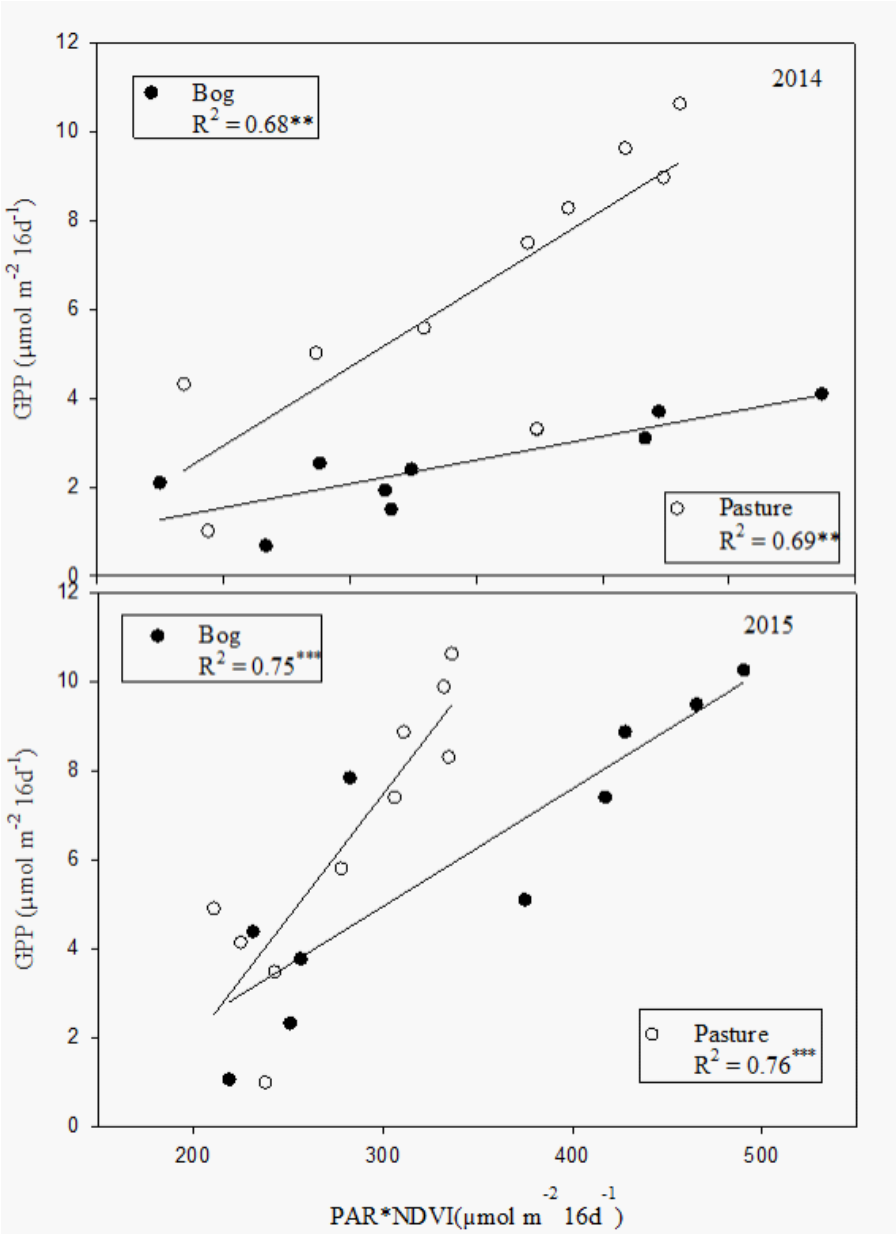

Figure 3.9: Relationship between the EC tower-based GPP and the product of PAR×NDVI (NDVI derived from MODIS and PAR from the EC tower-based measurements) during the 2014 and 2015 growing seasons (May-October) at the bog and pasture sites in western Newfoundland, Canada.

Asterisks indicate significance level of the relationship: **P < 0.01, ***P <0.001

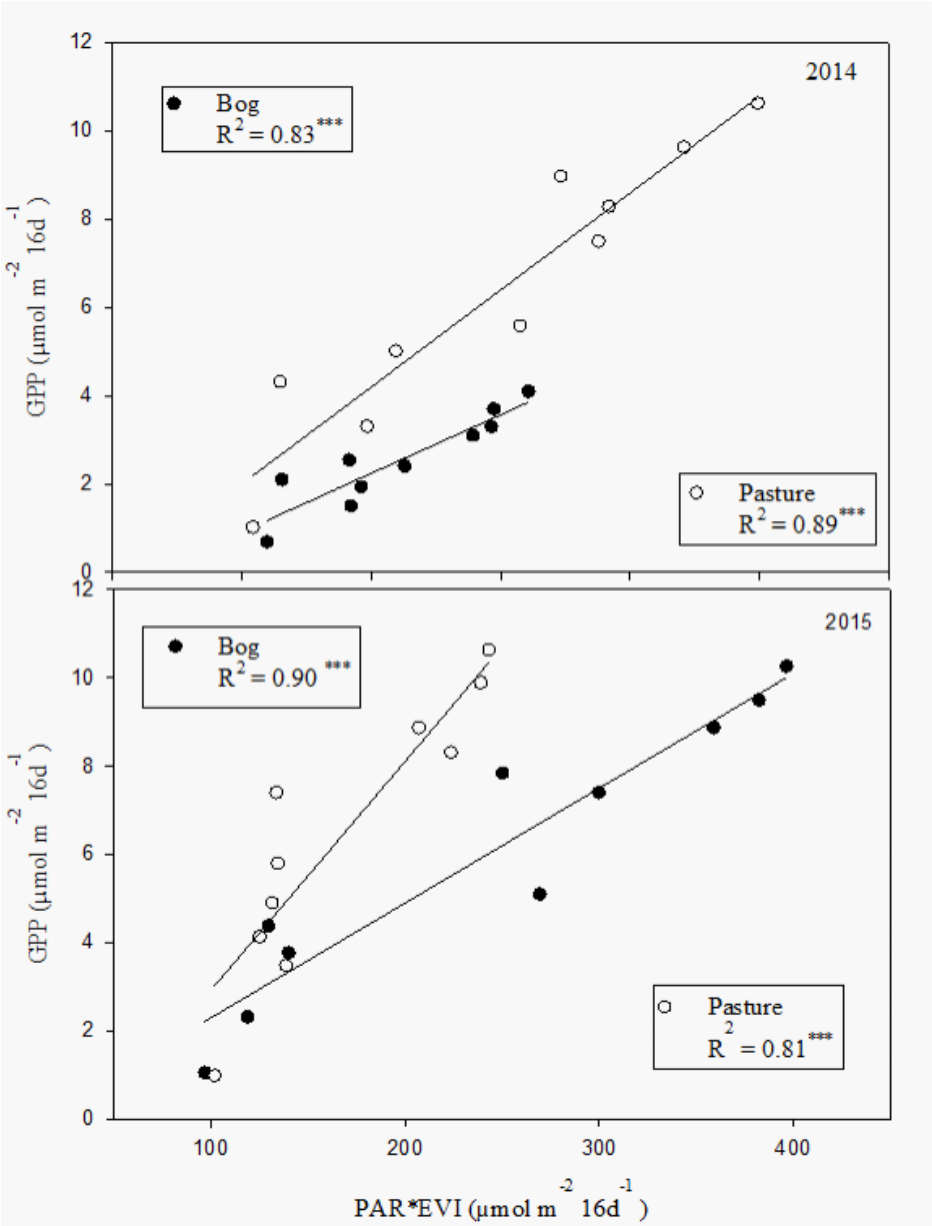

Figure 3.10: Relationship between the EC tower-based GPP and the product of PAR×EVI (EVI derived from MODIS and PAR from the EC tower-based measurements) during the 2014 and 2015 growing seasons (May-October) at the bog and pasture sites in western Newfoundland, Canada.

Asterisks indicate significance level of the relationship: ***P <0.001

3.5. Discussion

In the current study, I evaluated the efficacy of five different models (PAR, NDVI, EVI, PAR×NDVI, PAR×EVI) to estimate the GPP at the pasture and bog sites (Figure 3.6-3.10). My results revealed that vegetation indices can be used to better quantify the ecosystem GPP at the pasture and bogs sites in northern peatland compared to PAR alone, due to lower correlations between PAR and GPP (Figure 3.6-3.10). My results are in line with the findings of Olafsdottir and Oskarsson (2014), who reported that GPP and PAR had weak correlations ($R^2 = 0.35$) when estimating GPP in the terrestrial ecosystems (Olafsdottir and Oskarsson 2014). A weak relationship between PAR and GPP was also reported by other researchers when quantifying ecosystems' GPP (Nijp et al. 2015a; Wang 2017). Similarly, a weak correlation between PAR and GPP at the bog and pasture sites was noticed in this study for both study years (Figure 3.6).

VIs (NDVI and EVI) were found to be more promising than PAR alone while quantifying the ecosystem GPP under my study conditions (Figures 3.6-3.10). However, EVI showed significantly stronger correlations with GPP than NDVI when quantifying ecosystem GPP with remote sensing data at the pasture and bog sites in both study years (Figures 3.7-3.8). A higher relationship was recorded between EVI and GPP, compared to NDVI and GPP, showing that EVI is more sensitive to GPP compared to NDVI, as depicted in Figures 3.7 -3.8. Earlier researchers reported similar findings and showed strong correlations between EVI and GPP compared to NDVI in forest or agricultural croplands (Kalfas et al. 2011; Sims et al. 2008; Wagle et al. 2014; Wu et al. 2009; Zhang et al. 2003). There could be two possible reasons to explain the stronger performance of EVI compared to NDVI: Frist,

EVI was a better vegetation index to overcome the background disturbance, to minimize the effects of sky conditions, and to be very sensitive over high biomass areas (Wardlow and Egbert 2010); Second, EVI performed better due to independent natural environmental factors (i.e., temperature, humidity, wind, rainfall, etc.) compared to NDVI, which could be affected by changes in weather conditions, resulting in weak relationships with GPP in any ecosystem (Waring et al. 2006).

However, simple GPP estimation models based on VIs resulted in a lower accuracy of GPP measurements simply because they were based only on total VIs and ignored certain conditions, such as inactive photosynthesis periods or environmental stresses (Sims et al. 2008). As such, short periods of GPP variations due to short-term environmental stresses could not be calculated from VIs efficiently and could result in lower model accuracy (Gitelson et al. 2008). GPP is dependent on several factors, including vegetation greenness, temperature, PAR, soil moisture, etc. For instance, GPP is affected by leaf and canopy structure, which can be well estimated by VIs and PAR (Wu et al. 2010).

Therefore, any changes in vegetation greenness (or other factors) could adversely affect the GPP estimations when measured through only VIs (Sims et al. 2008). Therefore, consideration of such variations as plants' internal chlorophyll content or external factors (like PAR, water table depth, and temperature) is essential to estimating GPP more accurately. Gitelson et al. (2008) reported a weak relationship between GPP and VIs (NDVI) when GPP values exceeded 10 g C m^{-2} d^{-1} under moderate to high vegetation densities, which shows limitations in GPP estimation while considering only VIs. Similarly, the solar elevation angles also affect the VIs (NDVI, EVI) by affecting

vegetation spectral reflectance during growing seasons where vegetation is in a scattered form (Sims et al. 2006). Therefore, to improve GPP estimation based on remotely sensed data, the improved models can make use of VIs in addition to PAR, because PAR is absorbed by chlorophyll pigment, as well as helping in CO_2 fixation when absorbed by non-photosynthetic pigment in vegetation (Zhang et al. 2009). The important feature of the VI×PAR method was the removal of the uncertainties in PAR for the estimation of GPP, because PAR could fluctuate with respect to time and space (Xiao et al. 2004b), and this can be compensated by the inclusion of VIs. In particular, when the GPP estimation is done over a short time period (Sims et al. 2008), both PAR and VIs need to be used to capture both biotic and abiotic variations. In another study conducted by Olafsdottir and Oskarsson (2014), they also reported that PAR alone could not explain variation in GPP estimation. Therefore, PAR alone, or VIs alone, may not be a wise option to explain GPP variations. In this study, I evaluated the PAR× VI model for maximizing the efficiency of simulating GPP variation for more green vegetation biomass (Figures 3.9-3.10).

The present study has demonstrated that PAR×VIs models expressed higher accuracy for GPP measurements compared to VIs alone (Figure 3.6-3.10). PAR×NDVI also expressed greater correlation coefficients at both study sites during the 2014 and 2015 growing seasons (Figure 3.9) compared to using PAR or NDVI alone. However, more accurate GPP estimation resulted from the PAR× EVI model, which expressed better GPP predictions through higher correlation coefficients compared to the other four models (Figure 3.10). The higher coefficients of determinations (R^2: 0.70 – 0.90) demonstrated that GPP can be well estimated by considering the product of VIs×PAR (Figures 3.9-3.10). The proposed

model of VIs × PAR was based on the logic of Monteith (1972), who suggested that GPP can be expressed as a product of *f*APAR, PAR, and LUE, where both LUE and *f*PAR variables could be estimated from VIs. Schubert et al. (2010) also demonstrated that the product of PAR and satellite sensor-derived EVI could be used to explain the GPP variabilities in peatland ecosystems. Peng et al. (2013) also reported that the product of VIs (NDVI, EVI), and PAR resulted in a higher determination of coefficients R^2 for the GPP estimation. A similar method was also adopted by Sims et al. (2008) for a temperature and greenness model to estimate GPP, and they found that a EVI×LST (land surface temperature) model could be used as a proxy of PAR and EVI. When observed together, the results from previous and present studies demonstrated that VIs alone could not explain the GPP due to temporal variation.

The VI×PAR model was strongly correlated with GPP compared to VIs alone at the natural bog and at the pasture peatland sites. The relationship between EVI×PAR at the pasture site during 2014 was better than at the natural bog peatland, whereas in 2015, the EVI×PAR was well correlated with GPP at the natural bog site (Figure 3.10). These results suggest that VI×PAR could be a possible model for the estimation of GPP in both natural and pasture peatlands.

3.6. Conclusions

The results showed that the product of VI and PAR could provide excellent estimation of bi-weekly (16 days) GPP for both natural and pasture sites. The VI x PAR worked better in the peatland ecosystem, with a higher value of determination coefficient R^2 (0.70 to

0.90). The results were better when compared to those estimated from VIs alone (R^2 ranged from 0.56 to 0.79). Both PAR and VI can be observed consistently in a reliable and inexpensive way, and our results suggest that GPP can be well estimated from the product of these two parameters, i.e. PAR and remotely sensed VIs. This method would offer greater benefit for GPP modeling and spatial simulation of GPP in peatland ecosystems because both PAR and VIs are readily available from the remotely sensed data. A typical limitation of this method could be the matching of VI and PAR data at the exact same time and space. These results indicate the potential of using the MODIS observations for worldwide GPP estimation in northern peatlands. This study suggests that it is quite possible to estimate GPP at the regional and/or global scale for northern peatlands using the readily available remote sensing (RS) data, and to monitor the ecosystem function of C cycling of northern peatlands using RS data.

Chapter 4

4. Difference in light use efficiency between an abandoned peatland pasture and an adjacent boreal bog in western Newfoundland, Canada

4.1. Abstract

Gross primary production (GPP) at the canopy scale is an important variable to assess variations in the functional role of peatlands in the global carbon cycle, and GPP is greatly affected by light use efficiency (LUE). Direct determination of photosynthetic light use efficiency (LUE) from space would be especially critical to LUE-based models for estimating GPP and/or net primary production (NPP), which use information from remote sensing to model terrestrial ecosystem production. Furthermore, the knowledge of spatial and temporal dynamics in LUE is essential to scale up the site-scale measurement of GPP and/or NPP to regional and/or global estimation of GPP or NPP for northern peatlands. Only a few studies have estimated GPP in northern peatlands using LUE-based models because the spatial and temporal variability of LUE, and the effects of environmental factors on LUE in northern peatlands, are poorly understood, although LUE-based models have been successfully employed to estimate GPP in other terrestrial ecosystems. The objectives of this research were 1) to study how LUE varies between an abandoned peatland pasture and an adjacent boreal bog; 2) to investigate how LUE changed in the study years 2014 and 2015; 3) to examine how air temperature, water table depth and vapour pressure deficit correlated with LUE during the growing season. I used eddy covariance (EC) flux

and meteorological measurements to calculate LUE based on EC-derived gross primary production (GPP) and absorbed photosynthetically active radiation (APAR). The finding showed there was a significant difference in LUE values during the growing season of 2014 and 2015 between the bog site (0.028 ± 0.098mol mol^{-1}) and the pasture site (0.034 ± 0.0109 mol mol^{-1}). Furthermore, the pasture site showed significant year-to-year variation in LUE during the growing season; however, the bog site did not have significant year-to-year variation in LUE. The mean LUE value at the pasture site was 0.384 in 2014 and 0.315 mol mol^{-1} in 2015. The LUE variation strongly correlated with air temperature and water table depth in both growing seasons at the pasture site and at the bog site, but the LUE did not correlate with vapour pressure deficit. This study indicates that agricultural drainage significantly alters the LUE of boreal peatlands and that the drained peatlands need to be considered separately in LUE-based models for northern peatlands. Moreover, a longer period of study is needed to fully understand the temporal dynamics of LUE in natural peatlands.

Key words: Bog, Peatland pasture, Light use efficiency, GPP, APAR, Environmental factors

4.2. Introduction

The peatland ecosystem is one of the most efficient soil carbon sinks on the planet, and it has massive implications for feedbacks between the peatland carbon (C) cycle and the global climate system. Peat consists mainly of partially decomposed plants, such as

sphagnum moss, and is found in wetlands, such as bogs and fens (Williams et al. 2015). Peatlands play a key role in the global C cycle and climate system due to their abilities to persistently absorb C from the atmosphere and store large amounts of organic C in the soil (Dise 2009; Gorham 1991; Lund et al. 2012). Peatlands have been an effective accumulator of C for the last 10,000 years of the Holocene (Gorham et al. 2003; Vitt et al. 2000). Carbon acquisition in peatland ecosystems occurs due to the slow decomposition rate because of waterlogged, anoxic, and cold climate conditions. However, studying the C cycle in peatlands at local and global scales is problematic because of their faraway location and large area (Kross et al. 2016a); therefore, techniques that utilize remote sensing data to determine changes in ecosystem production and net carbon exchange would be very beneficial. Remote sensing can be used to calculate NPP over large areas (Ahl et al., 2004). While there has been significant effort to develop these types of tools for forest and cropland ecosystems (e.g. Turner et al., 2002, 2003; Ahl et al., 2004), peatlands have received little consideration.

The LUE model originated with the works of Monteith (1972, 1977), and has since been adopted by many in the remote sensing and carbon flux communities. While it can be viewed as a conceptual model, the LUE model can also be expressed in explicit, mechanistic terms, based on the underlying physical and physiological processes of light absorption and conversion. Conceptually, the amount of photosynthesis or primary production is largely determined by the amount of photosynthetically active radiation (PAR) absorbed by vegetation (APAR). This is further modified by the efficiency with which this absorbed light is converted to fixed carbon, light use efficiency (LUE). Loosely

speaking, the absorbed radiation relates to vegetation structure and pigment pools, and the efficiency term relates to physiology. The absorption and efficiency terms can be confounded to varying degrees depending on the underlying dynamic biological processes, and on the exact operational definition of APAR and LUE (Gitelson and Gamon 2015).

Different scholars reported on the effect of environmental variables on light use efficiency in northern peatlands (Kross et al., 2016b, Connolly et al., 2009, Schwalm et al 2006 Lindrothl 2007, Syed et al., 2006). Kross et al. (2016b) studied the effect of meteorological parameters on LUE variation and found that air temperature was contributing more to the variation of LUE in northern peatlands. Connolly et al. (2009a) studied the LUE parameter variability and maximum LUE with effect for environmental conditions for two contrasting Canadian peatlands. They found that temperature was a growth limiting factor on LUE variation compared to VPD. Furthermore, Schwalm et al. (2006) stated that LUE is used widely in scaling and modeling GPP in the contexts of large spatial scale. They examined the relationship between daily and yearly LUE with environmental variables in the wetlands of Canada. The most important factor controlling LUE variations were light and temperature. In another study, Lindroth et al. (2007) examined the factors controlling photosynthesis in four different mires in Sweden and Finland and found that temperature sensitivity was maximum for photosynthesis, and water table depth also explained the variation of LUE. Furthermore, Syed et al. (2006a) studied the environmental controls on ecosystem photosynthesis in a peatland ecosystem. They concluded that the ecosystem showed large seasonal variation in photosynthetic activity which was correlated with shifts in temperature, and both spring increases and fall decreases in maximum ecosystem

photosynthesis were well predicted by the mean daily air temperature averaged over the preceding 21 days. The same kind of research in a mixed coniferous forest, by Lagergren et al. (2005), reported that the light was effectively used at an average daytime temperature of around 15^{o}C. When the vapor pressure deficit was above 1400 Pa, the LUE was reduced by approximately 50%.

The LUE-based model is simple and physiologically based (Goetz and Prince 1999), and it can be a useful method for linking eddy covariance (EC) measurements of carbon fluxes and remote sensing (RS) data (Yuan et al. 2007a). Temporal and spatial variation of LUE in an ecosystem is an important parameter for associating environmental components and gross primary production (GPP). In most models, LUE is regulated by the most restraining environmental stresses that limit the photochemical reaction process, such as water, temperature, nutrient availability, and vegetation types. Consequently, LUE has significant spatial and temporal variation (Hilker et al. 2008). An accurate measurement of GPP/NPP therefore depends on an extensive understanding of the environmental effects on LUE and the attainment of reliable environmental data. These needs have hindered the further progress of the LUE method. Spatial variation in LUE is also a potential error source in these implementations (Behrenfeld et al. 2001).

Air temperature and water table depth (WTD) act as significant controls on the LUE dynamics, thus the CO_2 dynamic in peatlands during the growing season, so they are consequently important factors in regulating net ecosystem production (NEP). The low temperature and high vapor pressure deficits (VPD) reduce the LUE because they lead to

stomata closure in many plant types. Water table depth will affect the LUE because larger photosynthesis occurred when the water table was deeper (Gatis et al. 2016). Low temperature, high VPD, and nutrient stress, have also been shown to affect LUE (Running et al. 2004), but WTD is also an influential factor in photosynthesis (Gatis et al. 2016).

How these environmental variables affect LUE dynamics has been well studied in forest and grassland ecosystems. Nakaji et al. (2014) reported that in forest ecosystems, environmental variables (air temperature, vapor pressure deficit, and soil water content) showed a significant relationship with LUE dynamics. Furthermore, Chen et al. (2009) found that low temperature influences LUE in grassland ecosystems. However, there is limited information and very few studies on how environmental factors affect LUE variation in northern peatlands. To address this gap in research, the present study aims to investigate the spatial and temporal variations in LUE using EC tower flux measurements of the GPP and photosynthetically active radiation (PAR) and examine how the environmental variables affect LUE dynamics at two sites in northern peatlands.

The LUE model of gross primary production is generally given as

$$GPP = LUE \times APAR \quad (1)$$

In this equation, GPP stands for gross primary production, and APAR stands for absorbed photosynthetically active radiation.

In Canada, peatlands cover a large area, around 1.136 million km^2, the second largest after Russia (Tarnocai 2006). Pasture peatland covers an area of approximately 170000 km^2 in Canada (Oleszczuk et al. 2008). However, very few studies have focused on the environmental controls over LUE on disturbed and pristine peatlands. Numerous authors

have recommended that more research be required to examine the spatial and temporal variation in LUE in northern peatlands (Goetz and Prince 1998; Gower et al. 1999; Ruimy et al. 1994).

In this research, I attempted to address the knowledge gap for LUE differences at a natural peatland (hereafter called bog) and an abandoned peatland pasture (hereafter called pasture) and its temporal variation, as well as examine how environmental variables, especially vapor pressure deficit, temperature, and water table depth, affect the LUE dynamics. The objectives of the research were 1) to study how LUE varies between an abandoned peatland pasture and an adjacent boreal bog; 2) to investigate how LUE changes in study years 2014 and 2015; 3) to examine how air temperature, water table depth, and vapour pressure deficit correlated with LUE during the growing season.

4.3. Materials and Methods

4.3.1. Study site

The research sites are in Robinsons (48.264° N, 58.665° W), Newfoundland, Canada. According to the metrological station (Stephenville), the average rainfall was 1340 mm and the average air temperature was around 5 °C for the last 30 years. During the growing period in 2014 and 2015 (May to October), air temperature and rainfall averaged around 12 °C and 705 mm, respectively. The two research sites were in a peatland complex and consisted of bog and pasture peatland (Figure 4.1). The pasture was an ombrotrophic bog

before 1970, but it was converted into pasture peatland by a matrix of ditches that was 0.5 m in depth and 30 cm in width. The distance between ditches was 30 m. The forage grasses were planted at the time of drainage. Reed canary grass, other low herbaceous, graminoid plants, and numerous small and tall shrubs dominated the pasture peatland. After about 10 years of active agricultural management, the pasture was abandoned, but the drainage has still been active and effective since then. The natural bog is situated to the east of the pasture peatland. The bog consisted of hallows, hummocks, and pools, which were dominated by *Sphagnum* mosses and, to some extent, with gray reindeer lichens; the hummocks were dominated by shrubs, and the hollows by sedges.

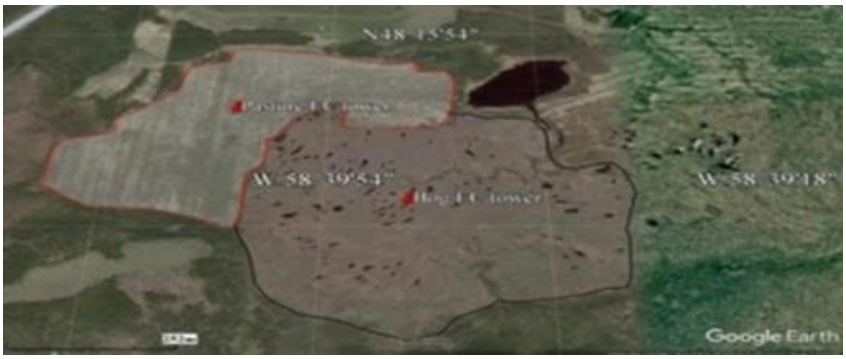

Figure 4.1: The study site of the bog and abandoned pasture in the Robinsons pasture, western Newfoundland, Canada, where the red pins indicate the location of the EC towers.

4.3.2. Eddy covariance measurements

Two identical eddy covariance (EC) towers were installed in the bog and pasture research sites. The details about the EC set-up and EC data processing can be seen in Wang et al. (2017). In the present study, only the gap-filled gross primary production (GPP) during the growing season was used. The GPP data was gap filled for 30 minutes from the EC tower

and calculated from an EC measured net ecosystem exchange (NEE) and ecosystem respiration (Re). GPP was calculated as

$$GPP=NEE-Re \quad (2)$$

To compute 8-day means (May-October) for non-gap- filled data, 30 minutes of GPP data over the daytime cycle were averaged.

4.3.3. Meteorological measurements

At both research sites, weather sensors were mounted on the eddy covariance tower or installed in the soil. The sensors measured different environmental parameters, including air temperature, relative humidity (RH), soil temperature and soil moisture, and water table depth (WTD). PAR was recorded by the quantum sensor (LI-190SL-50, LI-COR Inc., Nebraska, and USA). Two quantum sensors were installed, one of which was facing upward to record incoming PAR ($PAR_{incoming}$), and the other faced downward to measure the reflected PAR by canopy and soil ($PAR_{outgoing}$). Air temperature (T) and relative humidity (RH) were recorded with humidity and temperature probes (HMP155, Vaisala, and Vantaa, Finland). A stainless-steel transducer pressure sensor with an SDI-12/RS232 connection was used to measure water table depth (WTD). All environmental variables were scanned at the 5s interval and recorded as 30-minute means by a data logger (CR3000-XT, Campbell Scientific, Utah, USA) placed in a protected and cooled instrument hut. The average air temperature, WTD, and VPD was calculated over 8-day periods using data from every 30 minutes during both growing seasons at both study sites.

4.3.4. Calculation of absorbed photosynthetic active radiation (APAR)

APAR is an important component for LUE estimation. APAR was calculated by $PAR_{incoming}$ and $PAR_{outgoing}$ data (Nakaji et al. 2014), with the assumption that there is no transmission of PAR through soil and vegetation.

$$APAR = PAR_{in} - PAR_{out} \quad (3)$$

At both research sites, PAR data was recorded using downward and upward PAR sensors mounted on the EC tower during the 2014 and 2015 growing seasons (May-October). PAR_{out} represented the whole loss of PAR during the growing season at both the bog and pasture sites. The difference between $PAR_{incoming}$ and $PAR_{outgoing}$ is the actual absorbed PAR, which was used in the photosynthesis process. The accurate estimation of APAR is critical for the LUE calculation in bog and pasture peatlands in this study.

4.3.5. Estimation of LUE

The LUE was calculated to study its variation within sites and over years and as well to determine its relationship with air temperature, WTD, and VPD:

$$LUE = GPP/APAR \quad (4)$$

where LUE stands for light use efficiency, GPP for gross primary production, and APAR for absorbed photosynthetic active radiation.

4.3.6. Variability in LUE

The sub optimal weather conditions and maintenance costs of respiration are major causes of variation in LUE (Heinsch et al. 2003). Data on air temperature (T), WTD, and VPD were obtained from both the pasture and bog peatland datasets. Air temperature and WTD were taken directly from the measurement, but VPD was calculated using the equation (Snyder and Paw 2006):

$$es = 17.27\mathrm{T}/(\mathrm{T} + 237.3) \qquad (6)$$

In the equation, *es* is saturated vapor pressure and T is air temperature (^{o}C).

$$\mathrm{VPD} = [\mathrm{es}-(\mathrm{RH}/100) * \mathrm{es}] * 1000 \qquad (7)$$

RH stands for relative humidity.

4.3.7. Statistical Analysis

In order to attain my objectives, I used summary statistics to distinguish the variation of LUE over sites and a F–Test to demonstrate whether differences in mean LUE were significant or not between sites and between years. To examine how the LUE was related to AT, WTD and VPD, Pearson's correlation (r) was used to examine if any correlation between LUE and environmental variables was statistically significant. Statistical analyses were performed by Sigma Plot Version 12.0 and Statistics 8.0.

4.4. Results

4.4.1. Spatial Variation of LUE

Mean LUE data were divided into two different groups of statistics (Descriptive test, F-test: level of significance 95%): lowest values at the bog site (mean ± standard deviation,0.0289 ± 0.0098 mol mol^{-1}) and highest values at the pasture site (Mean ± standard deviation, 0.0347 ± 0.0109 mol mol^{-1}). The mean LUE values of the pasture and bog sites were 0.0347 and 0.0289 mol mol^{-1} respectively, and the sites showed a significant difference in LUE to each other (F-test: $p < 0.05$. Figure 4.2). The pasture site expressed significantly ($p<0.05$) higher LUE (0.0347 mol mol^{-1}) than the bog (0.0289 mol mol^{-1}), as depicted in Figure 4.2. The variation in LUE difference between the pasture and the bog during the growing season (May-October) in 2014 and 2015 is shown in Figure 4.3. The LUE almost followed the same trend in both study sites during the growing seasons; during the beginning and end of the growing season, the LUE values were the minimum, but during the middle of growing season (July-August), the LUE values were the maximum. In the pasture site, LUE values were higher than in the bog site.

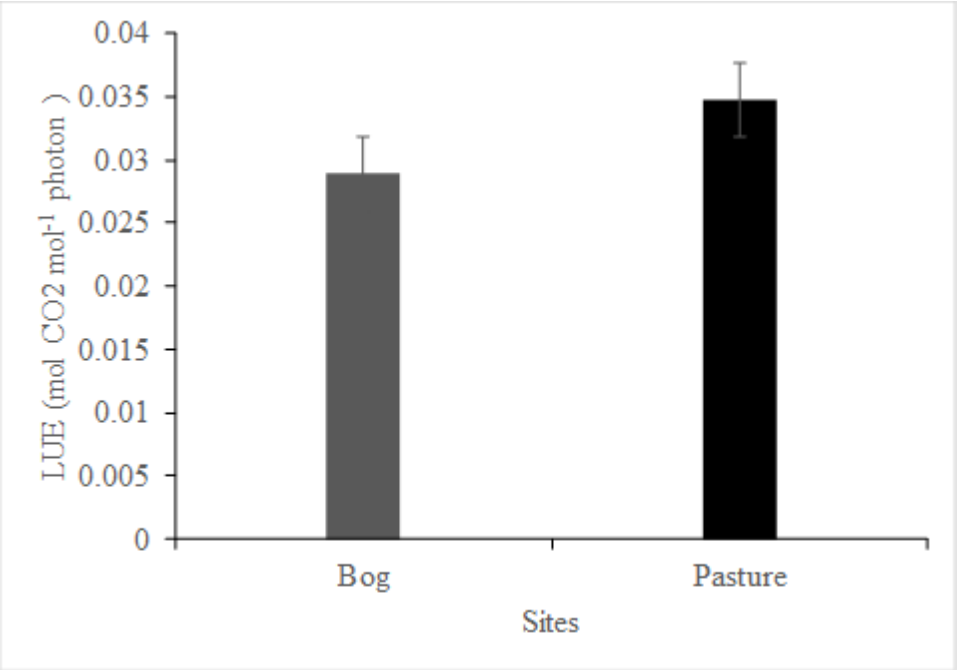

Figure 4.2: Mean LUE difference during the 2014 and 2015 growing seasons (May-October) at the bog and the pasture sites.

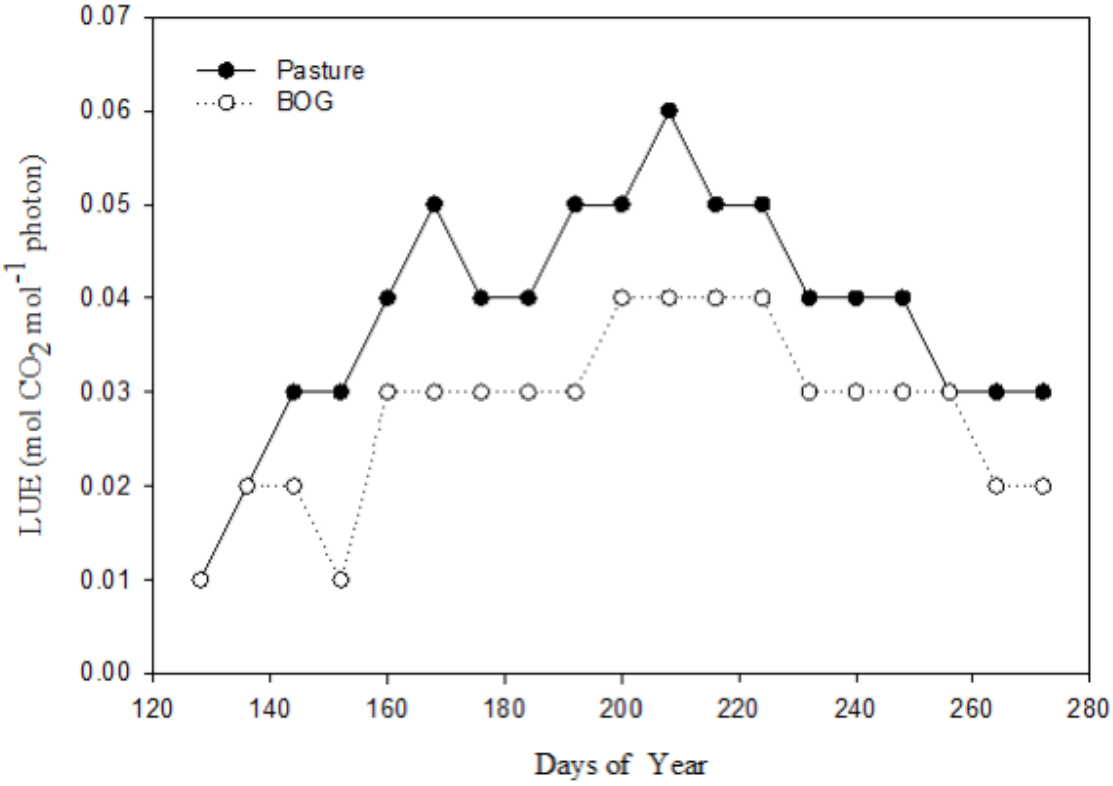

Figure 4.3: LUE variation during the 2014 and 2015 growing season (May- October) at the bog and pasture sites. The solid line represents the variation of LUE at the pasture peatland, and the dotted line represents the variation of LUE at the bog peatland. Each dot is the average LUE of the two years for that specific 8-day interval.

4.4.2. Temporal variation of LUE

During the growing season, the mean LUE value at the bog site in 2014 was 0.0278 mol mol^{-1} and in 2015 it was 0.029 mol mol^{-1}. The mean LUE value at the pasture site in 2014 was 0.038 mol mol^{-1} and in 2015 it was 0.031 mol mol^{-1}. The pasture site showed different LUE levels from those at the bog site in each study year. Furthermore, the pasture site showed greater variation in both study years (Figure 4.4), whereas the bog site showed less

variation in both years (Figure 4.5). The mean LUE at the pasture and bog sites showed significant differences in the two study years (F-test: $p < 0.05$). The mean LUE values at the bog site in 2014 and 2015 were not significantly different (F-test: $p > 0.05$), but the mean LUE at the pasture site in 2014 was significantly different from its mean LUE in 2015 (F-test: $p < 0.05$).

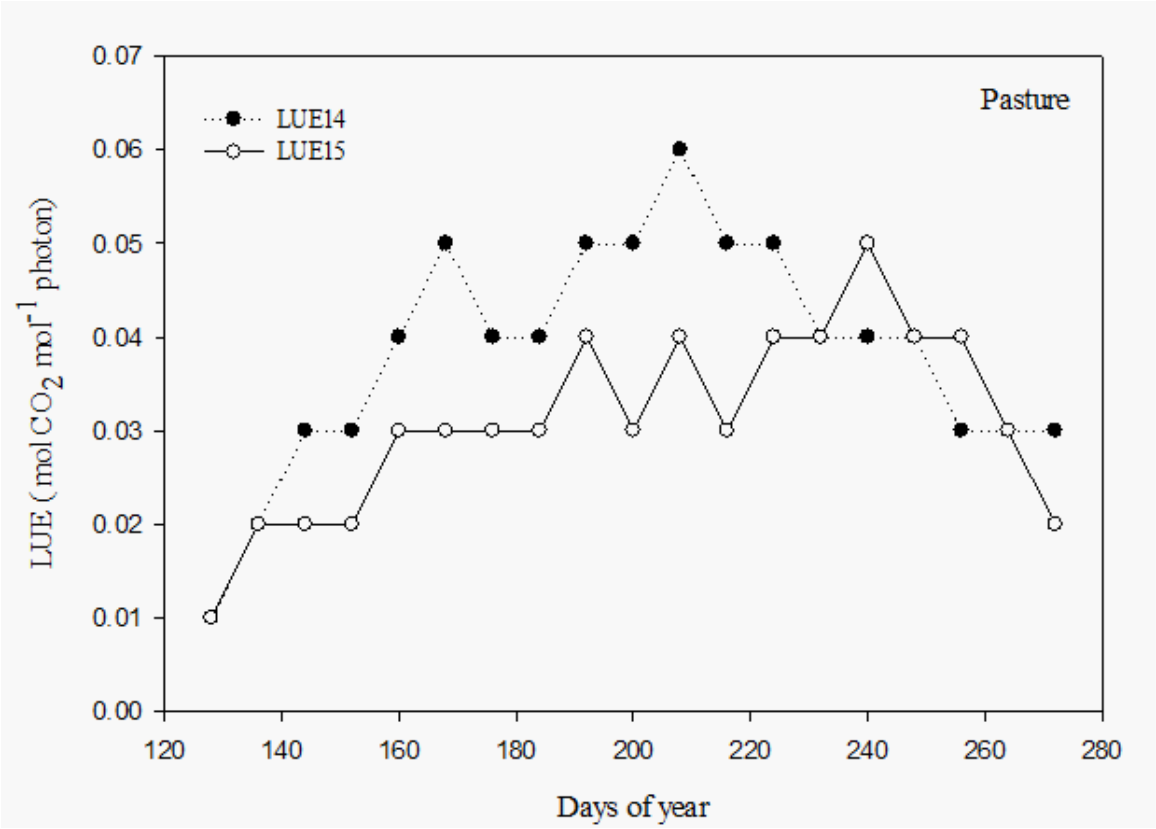

Figure 4.4: LUE variation during the 2014 and 2015 growing seasons (May- October) at the pasture site. The solid line represents the variation of LUE at the pasture peatland in 2015, and the dotted line represents the variation of LUE in 2014.

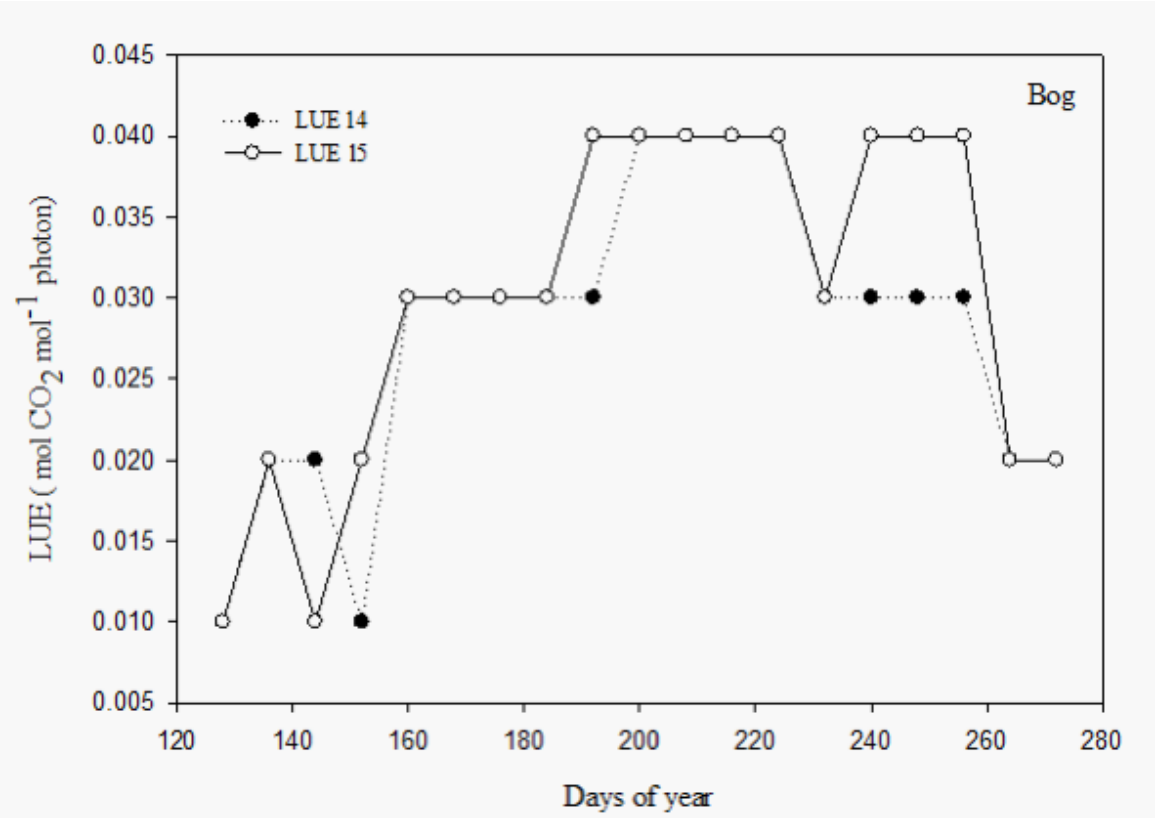

Figure 4.5: LUE variation during the 2014 and 2015 growing seasons (May- October) at the bog site. The solid line represents the variation of LUE at the bog peatland in 2015, and the dotted line represents the variation of LUE in 2014.

4.4.3. The correlation between LUE and environmental factors.

The LUE strongly correlated with air temperature ($r = 0.82$ $p < 0.00$) and WTD ($r = 0.72$ $p < 0.00$) at the bog site, but the LUE did not have significant correlation with VPD. At the pasture site, the LUE showed a strong correlation with air temperature ($r = 0.87$ $p < 0.00$) and WTD ($r = 0.74$ $p < 0.00$), but the VPD had no significant effect on the LUE at the pasture site (Figure 4.6 and Table 4.1).

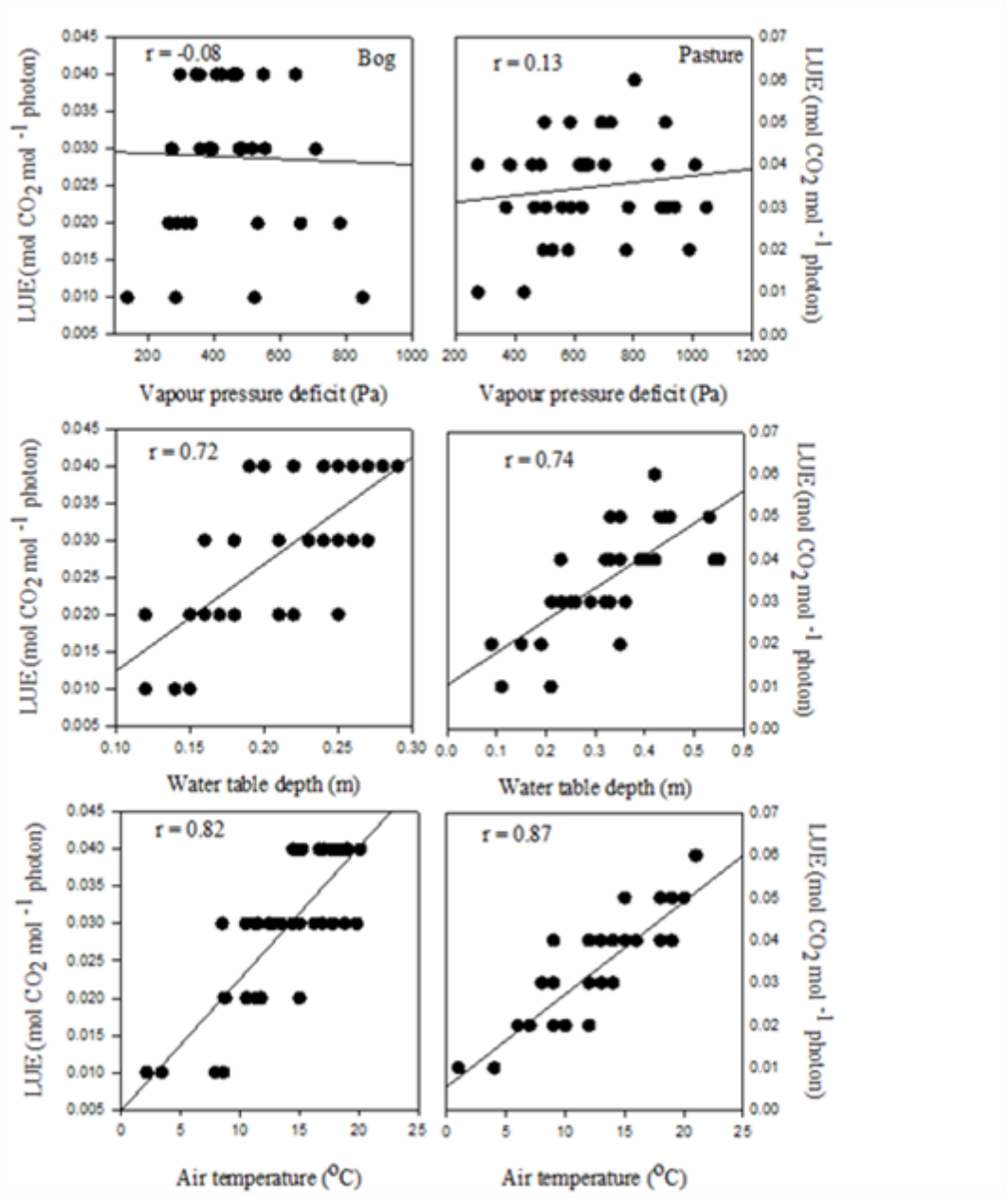

Figure 4.6: The correlation between the LUE and environmental factors (air temperature [T], water table depth [WTD], and vapour pressure deficit [VPD]) at the bog and pasture sites during study years 2014 and 2015.

Table 4.1: Pearson correlation between mean LUE_{site} and environmental factors

	Bog(n=38)		Pasture(n=38)	
	R	P	r	P
Air Temperature	0.82	0.000	0.87	0.000
Water table depth	0.72	0.000	0.81	0.000
Vapour pressure deficit	-0.08	0.061	0.13	0.401

4.5. Discussion

4.5.1. How did the LUE vary over time within each site and between the pasture and the bog sites?

The LUE was computed using the ratio of the EC tower flux GPP and APAR. In this study, the calculated LUE value ranged between 0.01 to 0.07 mol mol^{-1} (0.36 to 2.56 g C MJ^{-1}) at the pasture site. At the bog site, mean values of 0.01 to 0.04 mol mol^{-1} (0.36 to 1.46 g C MJ^{-1}) were observed. My calculations showed that the pasture site LUE value was higher than the bog site, whereas the range of the bog site LUE value was similar to other peatland LUE values.

Several studies have reported LUE values for peatlands based on GPP and PAR. For example, Schwalm et al. (2006) reported a median daily LUE value for wetlands as 0.65 ± 0.54 (median ± interquartile range) g GPP-C APAR MJ^{-1}. Connolly et al.(2009a) calculated

a mean growing season LUE ranging between 0.58 g GPP-C APAR-MJ^{-1} to 0.78 GPP-C APAR-MJ^{-1} (2000 to 2003) at the Mer Bleue bog, while at the Western peatland site the mean growing season LUE was 0.57 GPP-C APAR-MJ^{-1} in 2004. For two years, during a study of forest wetlands in Wisconsin (USA), Ahl et al. (2006) reported the variability of LUE values ranging between 0.28-0.31 g NPP-C APAR-MJ^{-1} and the mean growing season LUE varied from 0.37-0.41 g NPP-C APAR-MJ^{-1}. In my study, the pasture site had a LUE of 1.27±0.40 g C MJ^{-1} (0.0347 ± 0.0109 mol mol^{-1}) and the bog site had a LUE of 1.06±0.36 g C MJ^{-1} (0.0289 ± 0.0098 mol mol^{-1}). The LUE of the bog site is in a similar range of the LUE value at other peatland sites, but my pasture peatland site had a significantly higher LUE value than natural peatland sites (e.g., the bog site for this study and Connolly et al., 2009a and Schwalm et al., 2006). The mean LUE of 0.034 mol mol^{-1} was found for the pasture site, which was similar to that for a tall grass prairie with a recorded LUE value of 0.0308 mol mol^{-1} (Turner et al. 2003), but the mean LUE of the pasture site was a little bit higher than that of an alpine meadow with a recorded LUE of 0.019 mol mol^{-1} (Chen et al. 2009).

The maximum LUE was observed at the pasture peatland, not the bog peatland. There was significant difference in LUE between the pasture and the bog peatlands ($p < 0.05$, Figure 4.2), which may have been caused by the significant differences in vegetation composition and WTD at the two sites. The variation of LUE between the two sites could also be related to differences in plant species (vascular and non- vascular) and environmental factors. Variation in GPP could be more strongly influenced by LUE than APAR. The plant GPP rates in the pasture peatland were much higher compared to the GPP rates in the bog

peatland because the pasture peatland was dominated with grasses and other vascular species, which may have a much higher LUE. According to Strack and Zuback (2013) there was a positive correlation between GPP and vascular species in a reestablished peatland in Canada. The pasture peatland was dominated by fast-growing grasses with a much higher aboveground green biomass (Luan and Wu 2015; Wang et al. 2018), so, presumably, the GPP rate was significantly higher in the pasture peatland because of the significantly higher LUE at the pasture site than at the bog site—after all, the APAR at both sites were not significantly different. It is understood that LUE has a direct relationship with GPP; this is stated in the definition of LUE. Hence, we can conclude that if the APAR is similar at both sites, yet the GPP was greater at one site than the other, then the LUE was the sole factor influencing the greater GPP value.

Notably, WTD plays an important role in the photosynthetic process in peatland ecosystems. Deeper WTD can enhance the photosynthesis process (Gatis et al. 2016). The WTD at the pasture site (-0.55 m in 2014 and -0.42 m in 2015) was deeper compared to that at the bog site (-0.27 in 2014 and - 0.29 m in 2015). It may be postulated that the significant difference in WTD may have played a role in creating a significant difference in LUE between the pasture and bog site as well.

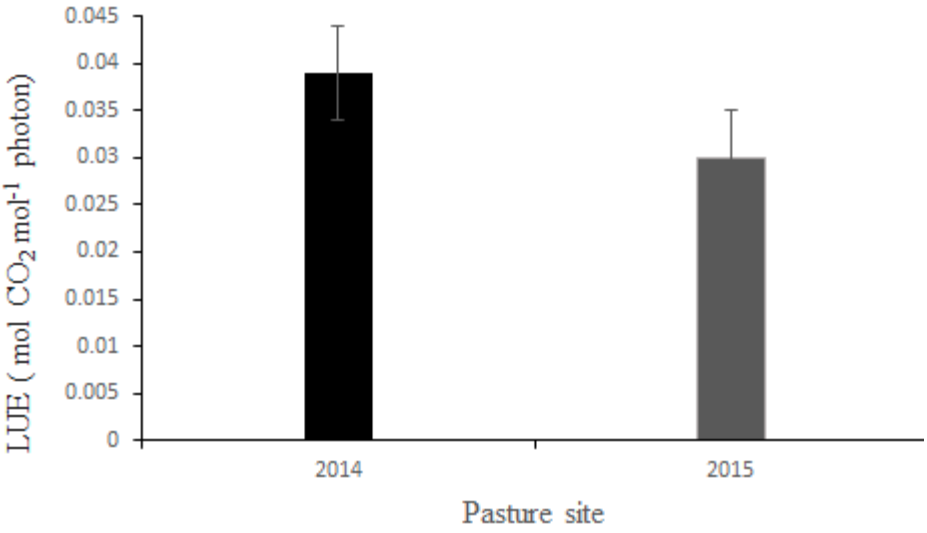

Figure 4.7: Mean LUE difference in the 2014 and 2015 growing seasons (May- October) at the pasture site.

LUE differences occurred in both study years and at both sites. The mean LUE values at the pasture site was significantly different between the study years of 2014 and 2015 (F-test: $p < 0.05$, Figure 4.7). The mean LUE values at the bog site were not significantly different between 2014 and 2015 (F-test: $p > 0.05$). The WTD was significantly different in both study years at the pasture site (F-test: $p < 0.05$, Figure 4.8). As depicted in Figure 4.6, WTD has a positive correlation with LUE at the pasture site. During the 2014 study year, the pasture site's WTD was lower (Mean ± standard deviation, -0.365 ± 0.108 m) than in 2015 (Mean ± standard deviation, -0.271 ± 0.100 m).

Deeper WTD has recently been found to increase the photosynthesis at a drained peatland (Gatis et al. 2016). In the present study, the WTD was found to be significantly different at the pasture site between 2014 and 2015 (Figure 4.8), which may have affected the LUE due

to its effects on GPP. According to Jarveoja et al. (2016), when WTD was lower at a restored extraction peatland, the result was a greater coverage of vascular plants and a lower coverage of non-vascular plants, which was due to the extended zone of aeration for plant roots. The higher percentage coverage of vascular plants was found to lead to a higher GPP rate at a restored peatland (Strack and Zuback 2013). In the present study, the GPP and LUE showed positive correlation at both study sites during both study years (Figure 4.9). When GPP fluctuated, this resulted in variation in LUE. The inverse relationship was found between LUE and APAR at both the bog and pasture site during both study years (Figure 4.9).

According to the WTD dataset, deeper WTD was recorded in 2014 at the pasture site, the same year that greater LUE values were found at that site, whereas WTD was found to be shallower in 2015 and in that year lower LUE values were recorded there (Figure 4.8).

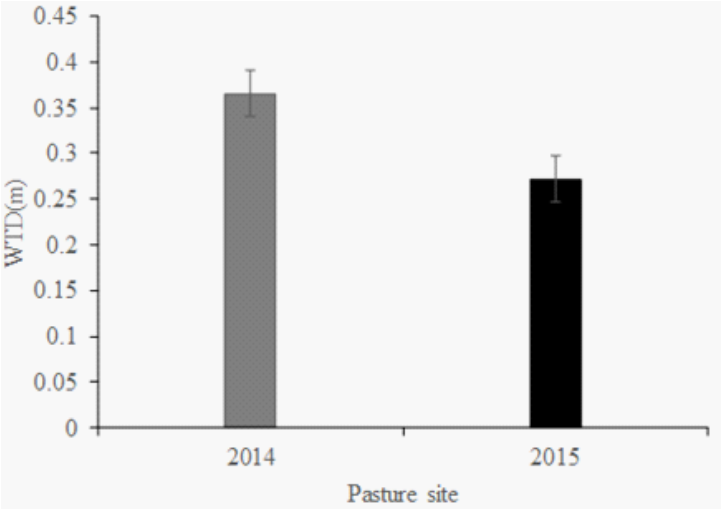

Figure 4.8: Mean WTD difference during the 2014 and 2015 growing seasons (May-October) at the pasture site (here the positive WTD indicates the water table below the ground).

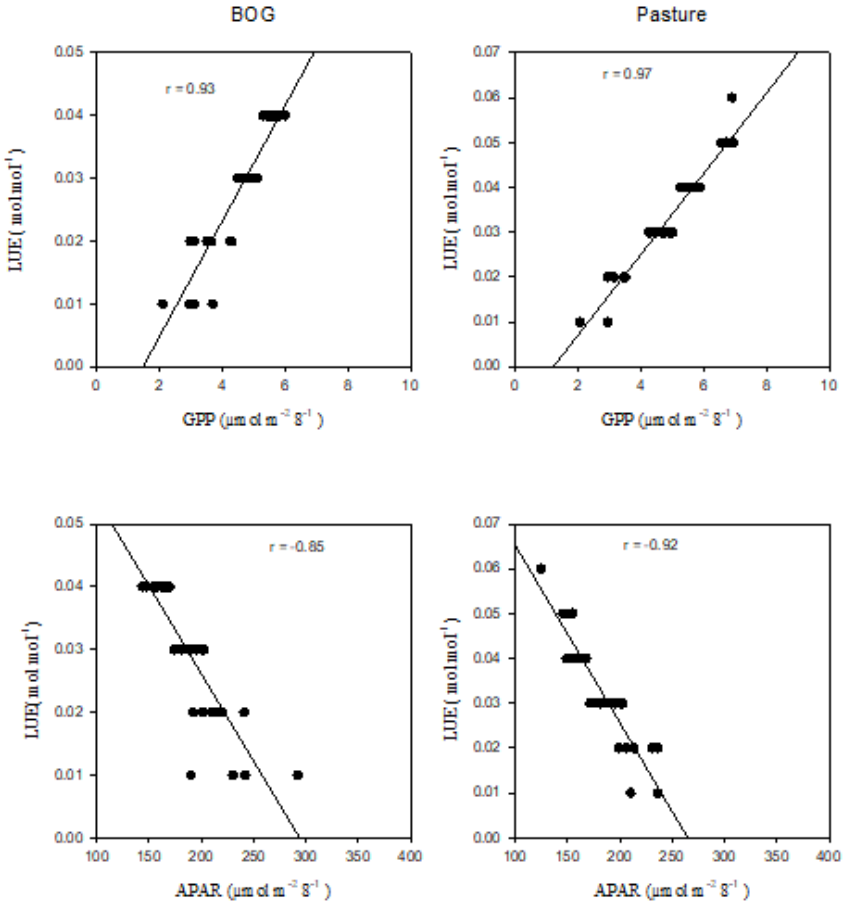

Figure 4.9: The correlation between LUE and GPP and APAR at the bog and pasture sites during study years 2014 and 2015.

4.5.2. How was the variation in LUE values affected by the changes in environmental factors?

LUE was significantly correlated with air temperature and WTD, but VPD did not show a significant effect on LUE for either the pasture or the bog site (Figure 4.6). Connolly et al. (2009b) reported that temperature is a limiting growth factor at the Mer Bleue and western peatland. When the temperature falls below -6 °C at the Mer Bleue and -10.6 ˚C at the western peatland, the plants' physiological processes stop, and LUE is then minimized to

zero, since the plants are not able to use sunlight to perform photosynthesis. Kross et al. (2016a) also explained that air temperature was a limiting factor for LUE in their research sites. Likewise, Syed et al.(2006b) reported that photosynthetic capacity in the western peatland ecosystem was strongly correlated with temperature and growing degree days during the growing period. The present study also demonstrated that air temperature was strongly correlated with LUE at the pasture and bog peatlands (Figure 4.6).

WTD was found to have a positive correlation with LUE at both the pasture site and the bog site (Figure 4.6). It was found that LUE increased with a deeper WTD. WTD alters LUE through its effects on GPP. According to Gatis et al. (2016), photosynthesis showed a positive correlation with WTD, and photosynthesis increased with a deeper WTD. A slightly drier condition was caused by the deeper WTD, which could enhance the above-ground biomass, but only if the deeper WTD did not reach a point where it restricted plant growth (Murphy and Moore 2010). This condition can encourage maximum coverage by graminoid, and graminoid (as opposed to mosses) has the ability to maximize the NEE rates (Otieno et al. 2009). Syed et al. (2006b) also observed that photosynthesis and ecosystem respiration were positively correlated with WTD at the western peatland.

VPD was not found to have a significant effect on LUE (Figure 4.6), which indicates that VPD was not a limiting environmental factor for LUE at both the pasture and bog peatlands. Connolly et al. (2009b) reported that VPD did not impose a significant effect on LUE at Mer Bleue or at the western peatland. Turner et al. (2003) also reported that VPD was not a critical factor for LUE at different biomes. They only found a weak inverse relationship between VPD and LUE ($r^2 < 0.30$) at all sites (agriculture field, hardwood forest, boreal

forest and tall grass prairie), but, notably, no peatlands were included in their study. Syed et al. (2006b) observed that greater VPD was found between noon and evening, and decreasing stomatal opening, due to the greater VPD, would decrease the CO_2 level in leaves, which might play a role in reducing LUE through photosynthesis in the afternoon. Waring et al. (1995) reported that LUE decreased when VPD ranged between 1.5 and 2.5 kPa, and LUE was reduced to zero when VPD was above 2.5 kPa. In the present study, the VPD value ranged between 0.5 and 0.9 kPa, which were comparatively lower values; however, both the drained pasture and the bog sites were found to have a relatively shallow water level, so VPD was not a limiting factor for the LUE in this study's sites, which is consistent with findings in other research sites. All studies, including the present study, suggested that environmental factors have an important role in LUE variation between sites and during the growing season.

4.6. Conclusion

The results showed that spatial and temporal variation in LUE between the sites may be caused by the vegetation composition and environmental factors at each site. The changes in LUE within sites were strongly correlated with air temperature and water table depth in both the 2014 and 2015 study years. The pasture peatland was the most active site (0.3474 ± 0.1156 mol mol^{-1}) for changing APAR into photosynthesis, the bog being the less active site (0.2895 ± 0.0981 mol mol^{-1}). The LUE commonly showed a weak measure at the start and end of the growing season in both study years. Previous studies only used PAR data for their calculations because of the absence of APAR data at those research sites. Further, the present study used the measured APAR data to calculate LUE, which helped obtain a

more accurate estimation of LUE in peatlands. This study would be helpful for improving our knowledge on the dynamics of LUE in peatlands, as this study's method could lead to better understanding the spatial and temporal variation in LUE and its environmental controlling factors, not only for peatlands but also for different biomes. The present study, which exhibits similar results to previously published studies, suggested that air temperature and water table depth are the two controlling environmental variables that regulate the spatial and temporal dynamics of LUE in northern peatlands. To the best of my knowledge, there has not been much research done on drainage pasture peatlands. This present research will be a path for future investigation on drained peatlands.

Chapter 5

5. Summary and conclusion

The objectives of this thesis were

a) To determine the variations in GPP and PAR at both an abandoned peatland pasture and a bog.
b) To draw a relationship between GPP and chlorophyll-related VI (NDVI and EVI).
c) To study the possible relationships between GPP and NDVI× PAR and EVI ×PAR.
d) To investigate the mechanism of changes in LUE in a natural bog and an abandoned peatland pasture during the growing period.
e) To study how LUE differs between a natural bog and an abandoned peatland pasture.
f) To examine the relationship between LUE and air temperature, WTD and VPD.

In chapter 3, the GPP values were reported to be higher at the abandoned pasture a site than at the bog site in both the 2014 and 2015 study years. During both study years, the temporal variation of GPP showed similar trends throughout the growing season at both sites. Also during both study years, PAR did not show similar trends in GPP patterns at either site. The VIs (NDVI and EVI) showed similar variation patterns at the pasture site during both study years, but at the bog site, both NDVI and EVI did not follow a similar trend. In the 2015 study year, GPP and PAR had a positive significant correlation at the pasture site, but a weak and non-significant correlation at the bog site. Furthermore, GPP and VIs (NDVI and EVI) exhibited significant positive correlation during both study years at both the pasture and bog sites. This study found that the strength of correlation between GPP and PAR×VI was significantly higher at the pasture and bog sites during both study years than that between GPP and PAR or VI alone. Hence, it was concluded that GPP could be predicted in a better way with the product of PAR and VIs. Overall, I found different temporal

patterns of GPP and PAR, and as well found a better way to estimate GPP at the bog and abandoned pasture sites (explained in chapter 3).

In chapter 4, I compared the spatial and temporal pattern of LUE at the pasture and bog sites. The pasture site showed a higher LUE capacity compared to the bog site. The mean LUE value at the pasture site was 0.0347 mol mol^{-1} and at the bog site it was 0.0289 mol mol^{-1}, and both sites showed a significant difference from each other (F-test: $p < 0.05$). As depicted in Figure 4.3, LUE variation patterns are similar at both study sites during both growing periods. At the start and end of the growing seasons, LUE values were lower, but at the middle of the growing season, LUE values peaked during both years at both study sites. The LUE variation is strongly controlled by environmental factors. The air temperature and water table depth correlated the LUE variations in both study sites during both growing seasons. VPD was found to be a non-significant factor in regulating the LUE variation at the pasture and bog sites during the 2014 and 2015 study years. Overall, I found that LUE varied spatially and temporally in peatland ecosystems. Until now, LUE values were considered to be constant in an ecosystem, but this study found that LUE values change during the growing season.

6. References

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